'GROUNDWATER AND SURFACE WATER INTERACTION FOR INTEGRATED CATCHMENT PLANNING'

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GROUNDWATER AND SURFACE WATER INTERACTION FOR INTEGRATED CATCHMENT PLANNING

CONTENTS

CHAPTER 2: LITERATURE REVIEW

CHAPTER 3: STUDY AREA

APPENDIX D: HOW TO

ABSTRACT

Integrated Catchment Management (ICM), defined as the design of intervention strategies encompassing and integrating the fields of hydrology, environmental, social and economic science, is vital in order to reach sustainable solutions on a catchment basis. Modelling lies at the core of the ICM process as it supports baseline studies and enables analysis of proposed intervention measures both for present day conditions and under future scenarios. Its core role in ICM leads to the need to develop modelling into a more comprehensive activity within which the design of a modelling approach, selection of tools and need for linkages can be thoughtfully matched to the requirements of ICM. Initial research revealed a gap in this area, leading to development of a Framework for Catchment Modelling Studies (FCMS) intended to create a staged and systematic approach that could be used as a template for development of modelling exercises that strike the right balance between ICM needs, project costs and the availability of human and technical resources.

To demonstrate the utility of the FCMS and populate it with application guidance, practical techniques and examples, technical research was focused on analysis of groundwater-surface water interaction in the Rio Salado Basin. This flatland of 175,000km^2, is located in the Buenos Aires Province of Argentina and features widespread groundwater-surface water interaction as the key driver of the flooding in vast areas of the basin. This flooding currently limits the potential for agricultural and livestock development of what is, economically, most important region of the country.

Research revealed that use of uncoupled groundwater-surface water models was inadequate to simulate observed flooding in a test area of the Rio Salado Basin, and a new program – iSISMOD - was developed by coupling MODFLOW (McDonald and Harbaugh, 1988) with iSIS (HR Wallingford and Halcrow, 1995) to permit dynamic coupling of both systems and support improved flood probability mapping.

The research concludes that adoption of an FCMS approach would provide scientists and engineers with a systematic basis from which to think through technical issues involved in the modelling cycle, and would facilitate improved decision making on key issues, such as when uncoupled models must be replaced by coupled models. This systematic approach is not only resource-effective, it is more importantly essential to support development of integrated catchment management plans that are sustainable.

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My thanks to the excellent tuition provided by my first and second supervisors: Prof. Colin Thorne (School of Geography) and Dr. Nigel Wright (School of Civil Engineering), who conducted and supported me throughout the entire research and life process logically comprised in a seven years study. I leave for last a special mention to Colin's family for their support during my several stays in Nottingham and my thanks to all that stayed by me at different times during this important part of my life.

FIGURES, TABLES & BOXES

List of Figures

Chapter 1

Chapter 2

Chapter 3

Chapter 4

Chapter 5

Chapter 6

Chapter 7

Chapter 8

Chapter 9

Appendix A

Appendix B

List of Tables

Chapter 2

Chapter 3

Chapter 4

Chapter 5

Chapter 6

Chapter 7

Chapter 9

Appendix A

Appendix B

List of Boxes (Chapter 8)

In science, and particularly in modelling, no “last word” should ever be allowed to become the “final word”

[Hillel, 1986, p.42]

To my parents, from who I learnt the passion for knowledge,

and

to my son Gonzalo, to who I hope to pass mine.

- CHAPTER 1 -

INTRODUCTION AND APPROACH TO THE STUDIES

1.1 Introduction

The past decades have witnessed an increasing awareness of the need to treat all water related issues in an integrated way and on a catchment basis. The concept of integrated catchment planning has been addressed by various authors from different perspectives. The need to examine land and water interactions was discussed initially by Chorley (1969) and more recently by Newson (1997). Mitchell (1989) looked at the interdependency of the water system with other natural and non-natural systems as a preface to the concept of sustainability, which the World Bank (Serageldin, 1995) made a fundamental requisite in all basin plans. Gardiner (1991) developed one of the first complete sets of general guidelines for basin management. He recognized the need to carry out studies to integrate various disciplines, such as hydrology, geomorphology, ecology, environmental assessment and engineering, within the context of strong public participation and stakeholder ownership of the plans. Gardiner's pioneering initiative was followed by research in various disciplines that started to expand and develop frameworks for catchment studies that could first be audited by international funding agencies and, second, successfully applied by planning agencies in the implementation phase of a Basin Plan. Examples of this type of approach include the approaches developed by the Universities of Nottingham, Newcastle and Southampton on geomorphic studies (1998), the approach to engineering studies used by the World Bank (see Thorne, 1988), the framework for wetlands evaluation

(Acreman and Adams, 1999), the Water Resources Planning Guidelines (Environment Agency, 2003), the guidelines for EIA by the World Bank and recently the framework for Channel Restoration (Soar, 2001).

Flooding, property damage and public safety, embedded in a framework of economic justification, were early drivers for the development of basin management plans. Subsequently, there has been a widening of the view of basin planners to include issues other than floods. Factors responsible for this trend include the increasing pressure that people are putting on water resources systems, an increase in water consumption, low level sewerage and treatment facilities in developing countries, reduction of fresh water recharge into groundwater due to a growing world wide urbanization, and rapid conveyance of stormwater flows. A further impact of these factors is the recognition of an increasing need to preserve and understand the functioning of wetlands with respect to the multiplicity of functions that they perform within the water cycle (Hollis and Acreman, 1994; Institute of Hydrology, Acreman and Adams, 1999).

Within the context of basin management, modeling has always been the main tool to provide results and assistance to decision makers; although its role, scope and complexity have evolved rapidly in recent times. Early, "black box" hydrological models (like the Stanford Watershed Model, Crawford and Linsley, 1966) were eclipsed by the inception of hydrodynamic models that came to dominate practice at the time of the evolution of high speed computers. The last two decades have seen mathematical models seek to represent physical processed as closely as possible through simulation of all mechanisms within the water cycle. Also, model complexity has increased due to the need to integrate results across disciplines. This has led to the appearance of a large number of complex models most of which are very data and simulation time demanding.

One of the issues that have always received significant attention within researchers and modelers is the interaction between groundwater and surface water. This started with early developments that coupled 1D surface water models with 2D groundwater models to simulate flood wave attenuation due to bank storage (Pinder and Sauer, 1971), and to analyze complex conjunctive groundwater and surface water hydrological schemes (Morita and Yen, 2002; Refsgaard and Storm, 1995). The need to understand and improve the simulation of groundwater and surface water (GW-SW) interaction is clearly linked to the general principles and drivers of integrated catchment management in terms of the need to analyze issues such as: conservation of wetlands, low flows in rivers and flooding due to the interaction of surface water bodies with shallow aquifers. The latter need is perhaps one of the applications that requires close attention in order to identify methodological approaches that are able to account for the complexity of large scale process (i.e. large return flow situations) but, at the same time, feasible for application to large catchment areas at a master plan level.

Finally, it should be pointed out that, despite the effort and progress made in attempting to represent catchment processes in a physically based way, there continues to be a lack of a sound framework within which to conduct modelling studies. Such a framework is needed to guide planners and planning agencies on which tools, techniques and methods to use, at what stages in the planning process different models should be used, and what would be the cost-effectiveness of each possible approach that could be adopted.

1.2 Research Aims and Objectives

In the context of the issues outlined above, this research focuses on two key modelling issues relevant to supporting water resources management at a catchment-scale level, in regions where the geographic and geomorphic characteristics promote the operation of large-scale physical processes:

(i) development of an outline framework for conducting modelling studies as part of Integrated Cachtment Management Plans, and

(ii) application and analysis of the proposed framework to support improved understanding and simulating the interaction between groundwater and surface water (GW-SW) processes, in particular those associated with large and complex geographies that increase the difficulty of simulating some of the physical processes.

The aim of the framework will be to provide a structured approach to assist scientists and engineers in defining modelling strategies as part of basin planning, providing sample techniques, outputs and recommendations for what type of modelling exercises should be carried out at each phase of a planning process. In particular the issue of when uncoupled models should be replaced y coupled models is evaluated.

As part of the research process, the following specific objectives were identified to guide completion of the work:

(i) define an outline methodology/framework to guide development of modelling studies in multidisciplinary and regional water resources projects,

(ii) investigate the effectiveness/usefulness of different ways of simulating the interaction of GW-SW processes, in particular when they differ from the conventional representation used in hill slope models due to the fact that they occur over large areas,

(iii) analyse the suitability of using comprehensive modelling packages (in terms of the number of hydrological processes simulated) versus simpler models whereas *ad-hoc* coupling has to be performed using customised interfaces or a GIS system, and

(iv) finally, related to the above, investigate the effect of scale, time and geomorphic issues.

These objectives can be expressed more simply as questions that should guide a planner when approaching the modelling discipline:

- What are the overall framework of the studies and the objectives to be achieved?
- What is the optimum strategy –in terms of modelling- for fulfilling the requirements of the project?
- How should I implement such a modelling strategy?

It is important to state that the focus of this research is not to develop a new model of catchment hydrology: As described later on this thesis there are already a large number of modelling tools that, with different degrees of detail, simulate selected components of the water cycle and, are suited to the needs of specific, practical requirements. Because of the existence of a wide variety of hydrological processes within a catchment, this research is focused on how to select and combine various types of approaches to produce a modelling strategy that suits the needs of catchment studies in representing a key physical process, such as GW-SW interaction, applied to large scale catchments that result in the operation of these processes at similarly large scales.

1.3 Setting of the Research

1.3.1 Physical Setting

The regional physical setting for conducting the research was the Rio Salado Basin, covering an area of 170,000km^2 in Buenos Aires province, Argentina (Figure 1.1). This is over half of what is the most important province of Argentina, in terms of its contribution to the national economy. It is a significant agricultural area, accounting for 25% of national grain production and 30% of national production of meat. However, the area suffers from persistent flooding events that affect a large proportion of the catchment and impose severe constraints on existing production levels and on realisation of the full economic potential of the region.

The Río Salado catchment is one of the most important lowlands in Argentina, with no more than 130m of difference in ground elevation between the sea and the watershed, 600km to the west. The low relief is interrupted only by the presence of two ranges of Precambrian hills (ascending to about 900m above sea level) in the far south of the region. The whole catchment has a landscape dominated by aeolian features overlain by more recent fluvial features, which reflects the more arid conditions that once prevailed in the region. The natural river and drainage system has not yet adjusted to the present, humid climate and it does not have the required conveyance capacity either in terms of drainage density or channel geometric properties. Consequently, flooding is important in terms of both duration and extent. The landscape of the eastern and central parts of the catchment is characterised by numerous lakes, wetlands and marshes (Region B) while complex relic dune fields dominate the terrain of the northwest area (Region A). The flooding situation has worsened since 1970 as more humid conditions have prevailed across the area. This has had a distinct impact in the Northwest and, as this subregion has changed from semi-arid to semi-humid, groundwater levels have risen by up to 7m in some areas and land-use has changed from predominantly pasture to arable. In summary, the Rio Salado catchment contains great natural complexity, associated with each of the several large sub-regions encountered within the basin, each of which is characterised by its distinct physical features.

The interaction of groundwater and surface water (GW-SW) in Region A is a key mechanism: (i) because it produces a series of typical features in the landscape, (ii) constitutes the driving force for causing flooding and waterlogging, (iii) provides the only source of fresh water for human consumption and, (iv) is a vital agent for maintaining wetlands in the area. Therefore, a test area was selected within this region as it provides suitable conditions to investigate different methodological approaches to understanding, representing and quantifying GW-SW interaction, in order to predict the existing frequency of flooding in the catchment and the potential impact of proposed management measures to reduce flooding while protecting wetlands.

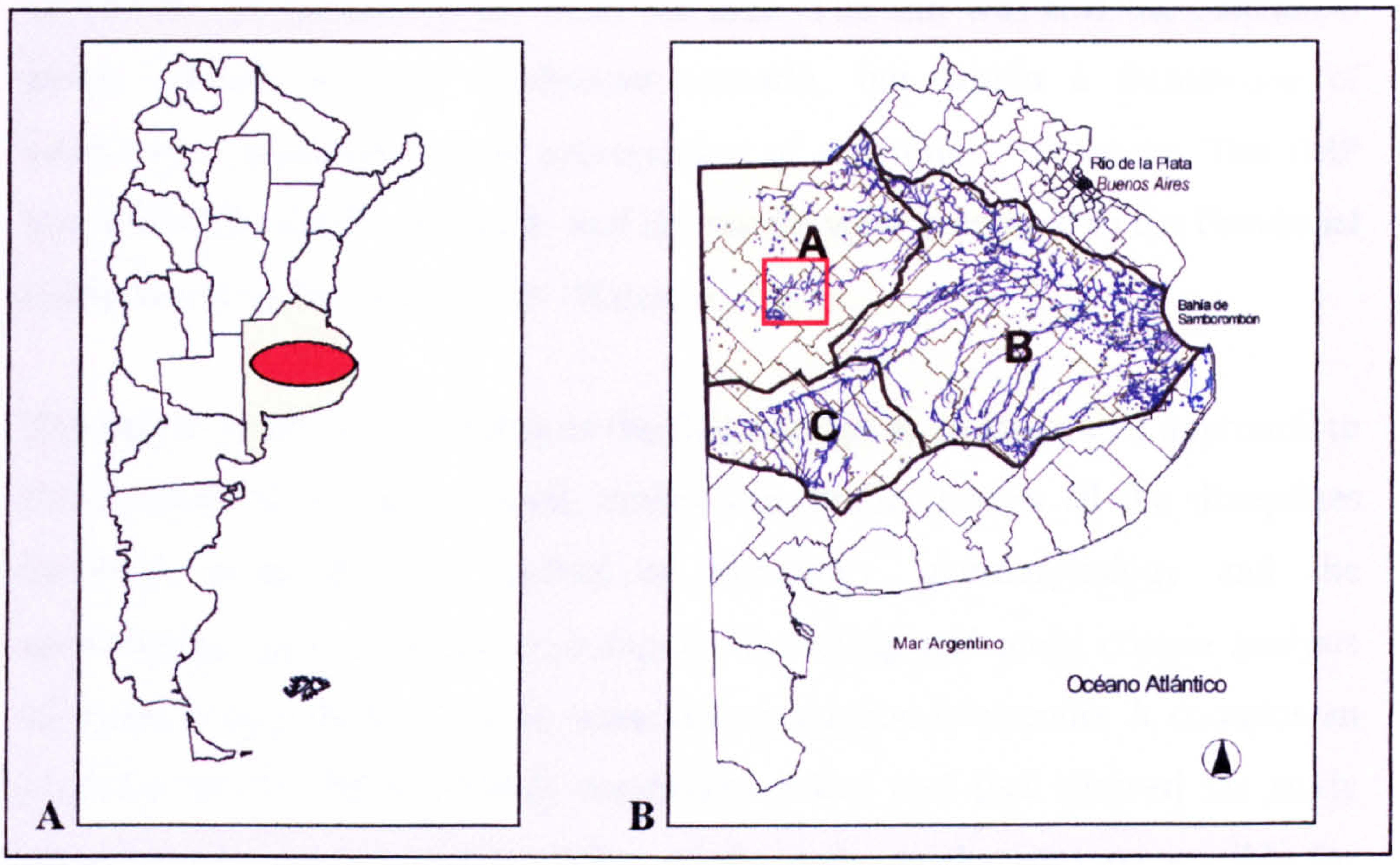


Figure 1.1: **A**: Location of Buenos Aires Province within Argentina. **B**: Location of Rio Salado Basin within Buenos Aires Province (A: Northwest Region, B: Salado, Vallimanca and Las Flores river valleys, C: South-Western Lake System. The red box shows the location of the test area within the Northwest region, A)

1.3.2 Planning Setting

The problem of flooding in the basin began attracting the attention of the Government at the beginning of the 20th century leading to several studies, with varying scopes and geographical extents, being carried out for the three regions independently (Figure 1.1). Key studies include AyEE (1990) for area A, CFI (1977) for area B and IATASA (1994) for area C. It is important to point out that, prior to some recent engineering measures being implemented, the Northwest Region (A) and the Western lake system (C) formed separate drainage systems without any connection or interaction with the natural drainage basin of the Río Salado (B).

In 1997, the Government of the Province commissioned development of an Integrated Master Plan (IMP) that would identify solutions to relieve flooding and waterlogging problems, and would in turn create more favourable conditions for farmers to invest in the area. The aim was that the catchment move towards a more productive scenario, but within a framework of sustainable management and preservation of environmental assets. The IMP was funded by the World Bank, and the results were presented to the Provincial Government in December 1999 (Halcrow, 1999).

The development of the IMP was the first attempt at an integrated approach to the problem at a regional level, comprising studies across all the disciplines involved, from baseline studies of hydrology, geomorphology and the environment, through complex computer modelling and multi criteria analysis of alternatives supported by an economic evaluation (Appendix A contains an overview of the IMP). Models constituted a key tool that allowed the study team to gain a good understanding of the main mechanisms responsible for producing flooding and waterloging and, consequently, to assess the potential impact of the proposed developments.

1.3.3 The IMP and this Thesis

The results obtained during the development of the IMP were used as the starting point for the research carried out and are presented throughout the different chapters to support the arguments of the thesis. During the three years of development of the IMP study, I had the role of Technical Coordinator and Deputy Team Leader, with specific leadership and direct involvement in the areas of mathematical modelling (groundwater and surface water), GIS, geomorphology and analysis of engineering measures prior to their inclusion in the Master Plan.

The development of the IMP, in relation to mathematical modelling, consisted in the development of separate regional rainfall-runoff (HYSIM, Manley, 1993), groundwater (MODFLOW, McDonald and Harbaugh, 1988) and surface water (iSIS, Halcrow and HR Wallingford, 1995) models to analyse the issue of GW and SW interaction highlighted in the previous section. The emphasis of the modelling work was placed on establishing links between the different model components to minimise overlap between the simulation of hydrological processes while also providing regional coverage and speed of execution in long term (33 year) simulations.

The outputs of both models were independently post-processed in a GIS system to derive flood probability maps representing the frequency with which each portion (pixel element) of an area suffers flooding. The frequency of flooding was calculated as the number of times (years) that the groundwater head and/or the surface water level exceeded the ground level, over the period of analysis (33 years in the case of the IMP). Such maps represent a synthesis of the model outputs and are fundamental to the appraisal that follows in either the diagnosis or planning stage of a project, as they lead directly to production of annualised economic benefits and identification of critical areas with high flood frequencies.

The methodological approach adopted in the IMP suited, in principle, the needs of a regional study at a prefeasibility level over a large and inhomogeneous catchment area. It permitted establishment of priorities between sub-regions and also supported economic justification of a set of structural measures for flood mitigation and land drainage. However, close inspection of the results obtained in the IMP for the test area, in term of its representation of flooding on the surface, indicates several shortcomings attributable to the weak representation of the interaction between GW and SW. Examples are: underestimation of flooded areas, under prediction of the frequency of occurrence of flooding, inaccuracy in the estimation of surface water heads and lack of ability to analyse proposed drainage measures and their associated environmental impacts in detail. Figure 1.2 presents a comparison of flooded areas as interpreted from satellite imagery for the largest flood event in the region (1987/1988) with those obtained from the regional model developed in the IMP. Identification of these shortcomings was the main driver for initiating this research. Identification of the need to devise a different, more detailed, methodological approach to represent large scale GW-SW interaction processes also led to the second major topic of this thesis: the design of a structured approach to conducting modelling studies, which includes consideration of scale, regional representation, regional homogeneity and model efficiency in relation to the needs (time and deliverable) of integrated catchment projects.

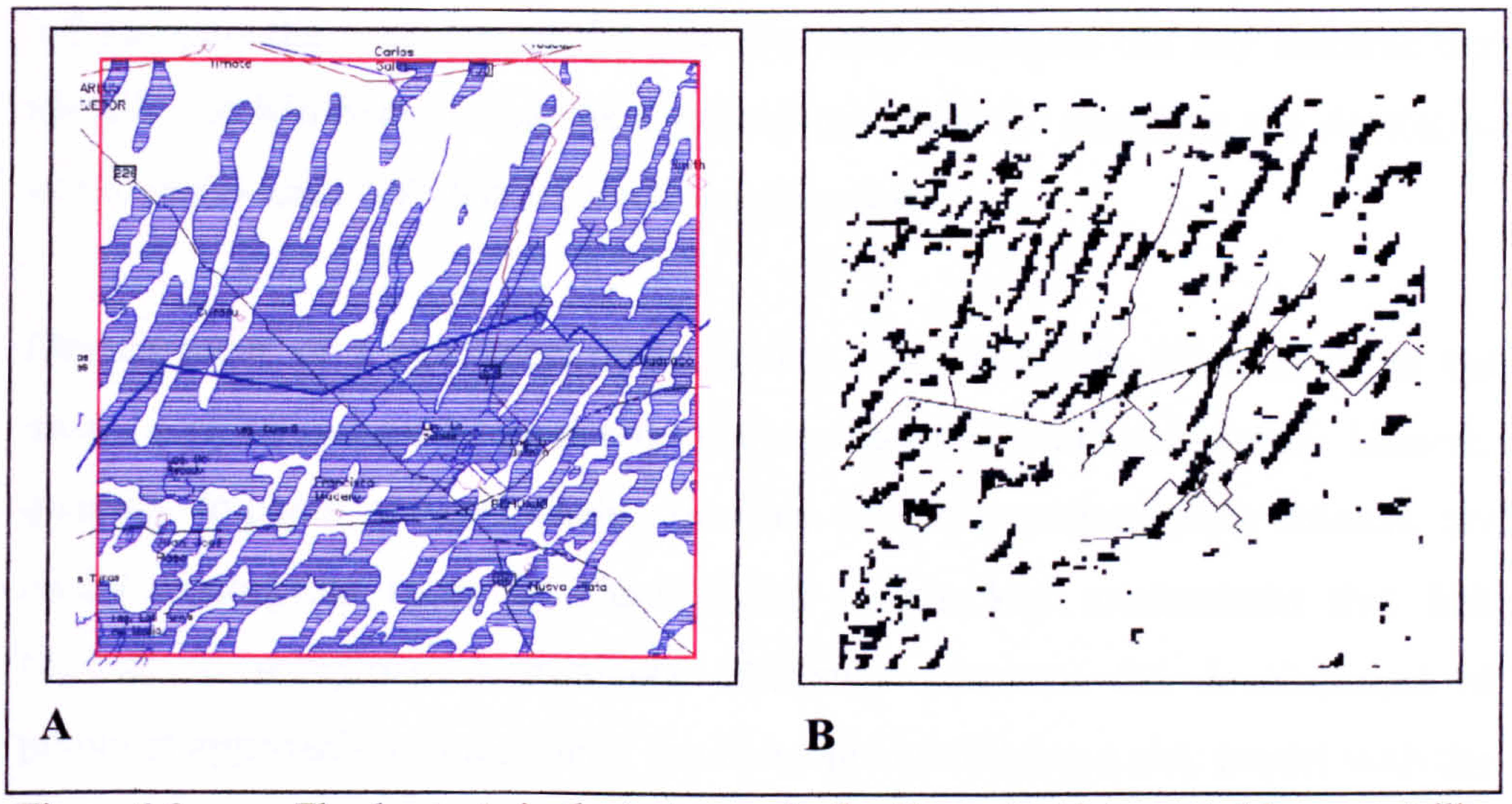


Figure 1.2: Flood extents in the test area. **A:** flooding extent interpreted from a satellite image for November 1987. **B:** flooding extent predicted by the Regional Model of the IMP.

1.4 Approach Adopted and Structure of the Thesis

The approach adopted in this research centred in addressing limitations, weaknesses and problems encountered in the modelling strategy used in the IMP studies for the Rio Salado Basin, with a specific focus on analysis of how surface water and groundwater interaction was addressed. The analysis and results, although preserving a regional vision, were focused in a test area within the Northwest region of the basin.

A comprehensive literature review was conducted (Chapter 2) to identify the relevant issues in the following topics: basin planning, integrated modelling frameworks and approaches for the simulation of groundwater and surface water interaction. The review also attempted to identify any existing tools that might be suitable for representing these processes when they occur at large scales and over large geographical areas.

Chapter 3 provides a full description of the geography and hydrology of the Rio Salado Basin, covering physical, social, economic and engineering aspects with the aim of developing an accurate characterisation of the hydrological mechanisms responsible for flooding and their interrelationship with the vital functions and roles of the basin. The chapter also presents the arguments that substantiate the selection of the test area, and highlights the key features that identify the Rio Salado basin as a suitable test case for analysing the simulation of the large-scale GW-SW interaction processes.

Development of a catchment management plan cannot be divorced from the need to carry out an integral risk analysis through which to identify hazards, quantify impacts and establish priorities for intervention. Risk models are useful conceptual tools to identify and isolate key mechanisms that link hazards to receptors. A particular challenge concerns the development of practical approaches to matching the concepts underlying a risk model with the need of practitioners to deliver practical solutions for the basin: Flood probability maps (FPM) constitute a key outcome that condenses the information from models in a form manageable by the the planner. Chapter 4 addresses conceptually the issue of FPMs and modelling approaches, establishing the starting point for PhD research and setting further, specific research questions that are subsequently answered through chapters 5 to 8.

Chapter 5 discusses the weaknesses of using a modelling approach based on the use of MODFLOW alone to generate FPMs. This was the approach adopted in the IMP studies to support diagnosis of the baseline situation and evaluation of the flood mitigation measures adopted. This approach, adopted at a regional level, was based on use of broad scale models with a simplified approach for coupling GW- SW processes.

As a consequence of those limitations, a new program was developed as part of this research (iSISMOD) to simulate, in a fully coupled manner, GW-SW interaction, making use of the existing software packages MODFLOW (McDonald and Harbaugh, 1988) and iSIS (Halcrow and HR Wallingford,

1995) to simulate GW and SW, respectively. Chapter 6 and Appendix B describe software development, the mathematical formulation of the new package, its functionality and the results obtained from its application in simple and conceptual test modelling exercises.

To confront the problems identified in Chapter 5, overcome them and draw general conclusions focused on the questions set in Chapter 4, several simulations were performed by applying iSISMOD to the test area. Chapter 7 presents the results obtained from these applications, allowing a discussion of results by comparing them with those obtained in Chapter 5.

The analysis of GW-SW interaction in the context of model application to a large basin and on a regional master plan leads inevitably to the analysis of two overarching issues: time and scale. These two environments generally need a different time step for their simulations due to the slower response of GW systems (Yen and Riggins, 1991). Also, GW-SW interaction implies dealing with shallow GW systems and, therefore, representation of surface relief features introduces another degree of complexity and opens the debate in terms of which is the suitable spatial resolution to use for the simulation of each system. Chapter 8 collects the findings from analyses carried out as part of the other studies, proposing an outline framework for structured modelling as part of Integrated Basin Plans, within which space and time scales issues are addressed explicitly.

1.5 Summary

This chapter has presented the overall framework and setting that support the research contained in the subsequent chapters, introducing the three overarching topics that substantiate the contribution of this thesis to hydrological science:

- *Scale of hydrological processes.* GW-SW interaction is a key hydrological process responsible for generating large groundwater-induced surface flooding. This process, commonly referred to as saturation return flow in the description of hydrological processes in hill slope catchments, takes on un-precedent importance in the Río Salado basin due to the magnitude and duration of its occurrence. Events are characterised by the large *extents* and huge volumes of water at the surface, the long *duration* of standing water in the surface, the *dynamics* of the return flow across the surface which vary from large-scale ponding to large-scale runoff situations.

- *Scale of the area.* The Río Salado Basin constitutes a suitable test case for analysing the occurrence of large-scale GW-SW interaction. The existence of dune fields -that extend over 50,000km^2 in Region A- superimposed on a generally low relief landscape, determines two of the necessary ingredients for the occurrence of a large return flow situation: negligible horizontal groundwater flow and geomorphic features controlling the dynamics of water at the surface. The existence of other large sub-regions within the basin (mainly within region B), each of them characterised by a particular flooding mechanism, adds a further degree of complexity. The danger exists that inadequate understanding and management of water resources in one region could trigger new large scale flooding problems, such as fluvial flooding along the corridor of the Río Salado.

- *Outline framework for modelling studies.* The need to deal with large-scale processes (both *understanding and modelling them*) as part of the process of catchment planning (implying *management* of those large scale processes) further reinforces the importance of structuring an approach to devise a modelling strategy that is able to support decision-makers throughout the process of performing an integrated appraisal of intervention options.

A focus of the three key points summarised above is sustained throughout the thesis, as the research explores the theme of GW-SW interaction. Chapter 2 addresses *why* the theme is important in the context of integrated catchment management, Chapter 3 describes *where* GW and SW becomes a dominant mechanism and Chapter 4 expresses GW-SW interaction through a practical and tangible product (the FPMs). Chapters 5, 6 and 7 analyse *how* to address this issue in practice, while Chapter 8 uses this theme to propose a new and comprehensive framework for modelling studies performed to support integrated catchment planning.

- CHAPTER 2 -

LITERATURE REVIEW

2.1 Introduction

The research covered in this thesis focuses on groundwater and surface water interaction, not as an isolated topic but within the wider concept of integrated catchment management. The literature review is a key part of the research as it provides a backdrop to the studies based on coverage of the current practices and developments carried out in each particular discipline, helping to put the new proposals in the correct context and perspective.

The review follows the logic of the research and therefore starts by examining key issues related to integrated catchment management, the range of disciplines involved and the importance of approaching GW-SW interaction in an integrated manner. A preliminary assessment of GW-SW interaction leads rapidly to the conclusion that the importance of such mechanisms is mostly related predominantly to areas of low relief. This is follows from the fact that there are key conceptual differences between the way that the hydrological cycle operates in hillslope and flatland environments (Mull, 1983; Paoli and Giacosa, 1983). This topic is further investigated through reference to international case studies such as that in the Río Salado Basin (Argentina) and in the Florida Everglades (United States).

GW-SW interaction is the central issue of the research reported here and, therefore, a section is devoted to analysis of the different approaches encountered to account for this interaction in a modelling exercise. The review includes consideration of theoretical developments, different numerical solutions and applications, such as those developed as part of MODFLOW

(River, Stream, Lake and Wetland) and development of other, more complex, coupled models such as MODBRANCH, SHETRAN, ISGW (based on the HSPF model) and the South Florida District Water Management Model.

The last section of this chapter ends with a discussion that summarizes the key findings of the review in relation to the development of a coupled GW-SW model, iSISMOD (Chapter 6). Also, the learning experience that emerged from the literature review supported extraction of key concepts needed to develop a framework for modelling studies (Chapter 8) within which the GW-SW interaction constitutes a key element.

2.2 Catchment Modelling within Integrated Catchment Management.

2.2.1 Integrated Catchment Management: what and why?

The concept of integrated catchment management (ICM) is today widely used and recognised as essential to guaranteeing that natural resources are managed in a sustainable manner. Various authors have supported this argument during the last thirty years, for example: Leopold and Dunne (1978), Saha and Barrow (1981), Mitchell (1989), Gardiner (1991), Serageldin and Steer (1995) and Newson (1997). Added to other publications by European research bodies and organizations (in the form of frameworks, manuals and review studies), these papers constitute a strong array of material and set the topic as a key item on the research agenda for this century.

Practising catchment management (previously also termed river basin planning) can be traced back for more than 9000 years, driven by the prime objectives of food gathering and dam construction. Saha and Barrow (1981) point out that it was not the concept that was new in the mid-twentieth century, when ICM first appears in the literature, but it was the acceleration of dam building and the complexity of the task of river basin development that stimulated a burst of publications. A key milestone, frequently quoted in references on ICM (Saha and Barrow, 1981; Mitchell, 1989; Newson, 1997), was creation of the Tennessee Valley Authority (TVA) with the firm intention to put into operational practice the theoretical concepts of ICM. This process was driven by merging three independent concepts: development of multi-purpose projects, treatment of drainage basins as a unit and state intervention to promote social change. The idea behind development of the TVA was the establishment of catchment protection measures so that allocation of the benefits of the increasing number of power generation enterprises was maximized, by developing a suitable market across the basin.

Modern issues have moved away from the concept discussed by Saha and Barrow (1981) as the "complexity" of catchment planning is now mostly driven by a number of interrelated factors other than just the construction of dams, such as demand pressures over water resources, water (quantity and quality), water scarcity and deterioration of the overall ecological status of environmental assets. Quoting figures from the World Bank (Serageldin and Steer, 1995): 1 billion people (nearly all in developing countries) do not have access to clean water, 1.7 billion people lack sanitation, 2 to 3 billion children die annually as a result of diseases associated to these problems, and 90 million people are added to the global population every year, doubling the requirement for food production in the next 40 years. These facts have boosted awareness of the need to preserve ecosystems, in view of a potential lack of resources to cover future needs.

In the late 1980s the concept of integrated catchment planning started to be logically coupled with the issue of sustainable development, brought into scene by the World Commission of Environment and Development in 1987 (The Brundtland Commission), as the "development that meets the needs of the present generation without compromising the needs of future generations". This was further addressed in Agenda 21 (World Bank's World Development Report, 1992), where the positive link between environmental and development issues was clearly recognised by all parties, "after decades of pitting environmental quality against economic growth".

The definition adopted in the Harmon IT project is illustrative of the current view of ICM. By this definition, ICM "*is the management of water as a whole on a river basin basis, including surface water, groundwater, transitional and coastal water, considering quantity, quality, ecology and economy, and involving all stakeholders in decisions*".

2.2.2 Integrated Catchment Management: how?

The sources cited above make clear the existence of a high level of awareness in terms of the need to carry out integrated catchment management and a good understanding of the principles and conceptual aspects associated with it. However, how to put ICM into practice is a matter of current and continuous debate, although there are already examples of holistic (and independent) approaches in various areas covered by the water management field, such as Flood Defence Studies, Urban Drainage and Water Resources.

The debate on practical aspects related to the implementation of ICM strategies is clearly addressed by Michell (1989) who warns that, unless the concept of ICM is defined clearly, it will be difficult to establish goals and targets, and ultimately, to monitor progress. The key contribution by Mitchell (1989) is to stress that, although the theory of ICM prompts examination of the broadest range of variables covered in the land and water management cycle, a staged approach should be followed to guarantee a timely and cost effective planning process. Mitchell (1989) goes onto state that integrated water management can be contemplated in at least three ways:

a) water as a system on its own, i.e. from a physical perspective from which the concept of integration springs from understanding the interrelation between each component of the hydrological cycle;

b) water as a system that interacts with other systems such as land and environment, i.e. that managers not only have to be aware that a given activity may have a detrimental impact on a component of the hydrological cycle but also it may affect other natural systems such as wetlands and floodplain habitats. This perspective is clearly broader than the first; and finally

c) water as a system that interacts with other non-natural systems such as economic and social development. This last, and even broader, approach considers whether water is an opportunity for, or a barrier against, development and therefore is the beginning of the sustainability concept.

Also, Mitchell (1989) sets up very clearly the scope and the level of analysis necessary for an integrated approach as a parallel classification to the above scheme: **a normative level, a strategic level and an operational level,** recommending progression from one to the next when planning the management of water and land resources. While at the strategic level it is important to think *comprehensively*, by taking into account all possible variables and scenarios that may influence a development situation, at the operational level the analysis should be more *focused* on trying to answers questions such as *"what will be done"* rather than *"what can be done"*. Furthermore, Mitchell suggests the use of the word *comprehensive* to refer to the strategic level and *integrated* to refer to the operational one. In the latter, the focus is placed onto a smaller number of variables that can account for a large portion of the management problems. This concept sets the basis for considering a staged modelling approach to catchment studies, as explained in Chapter 8.

The operational issue of ICM, in relation to the broadest category of Mitchell (1989), is also addressed by the World Bank (Serageldin and Steer, 1995) who state that sustainability cannot be put in practice unless a better integration is achieved between the viewpoints of three disciplines: economy, ecology and sociology. The key point highlighted in the quoted work is that, despite the fact that individual experts agree that the concerns of other disciplines matter in elaborating a sustainable approach, "*they do not see these concerns through one another's eyes*". For example, Figure 2.1 presents an example of how an economist expresses his or her particular views of other disciplines.

In fact, those viewpoints will not relate to the common objective of reaching sustainability unless a clear and unified methodological approach is devised to value the different, and often conflicting, objectives encountered in the planning exercise at a basin level. A cost-benefit analysis seems to be a way to establish the relative importance of the different issues involved, but with the drawback of having to assign cost and benefits to environmental effects and assets. This difficulty will prevent development of fully integrated approaches and the tendency of examining measures on a single domain (discipline) basis will continue (HR Wallingford, 2002). A similar view can be perceived in the analysis made by the World Bank (Serageldin and Steer, 1995) in which the issue of valuation, and in particular of the environment, was identified as a key problem to be overcome in reaching the desired, unified, methodological approach.

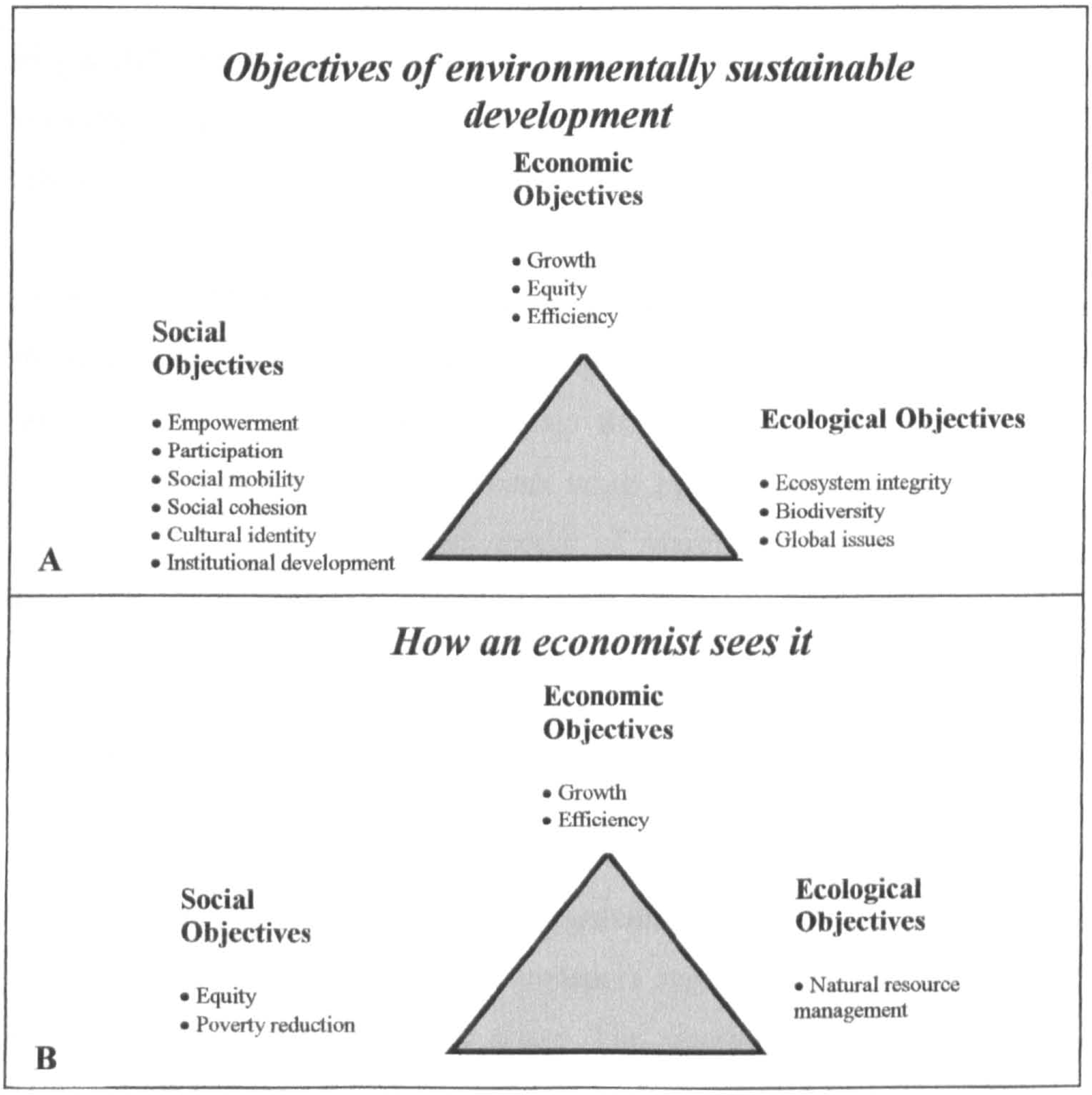


Figure 2.1: **A**: Objectives of environmentally sustainable development. **B**: How an economist sees it (reproduced from Serageldin and Steer, 1995).

In addition to the debate on how to translate theory into practice in ICM, another discourse concerns the regulations and water policies that exist across the World, such as the Water Framework Directory enacted by the European Union (EC, 2000). The WFD aims to protect all types of water bodies, bringing together the planning and management of water in a holistic way. WFD legislation only sets objectives, leaving the difficult task of establishing practical methodologies for analysis and implementation to the different planning agencies. In fact, the WFD does not actually provide a definition of integrated water management and neither does it prescribe methods for modelling.

2.2.3 Integrated Catchment Management: where?

In parallel with the increased awareness of the need for ICM, planners and authorities are aware that studies and strategies need to encompass the entire catchment.

Newson (1994) adopts the approach of Mitchell (1989) presented in the previous section, adding that the coupling between land and water is vital and has to operate at all levels: ranging from strategic (comprehensive) to operational (integrated). The approach taken by Newson (1997) to analyse a basin is based on the ecosystem model of Marchand and Toornstra (1986) structured on the natural regulation functions of a catchment, as follows:

1. regulation of water regime (terrestrial and climatic);
2. regulation of erosion and sedimentation;
3. water purification.

Newson defines the drainage basin as a systematic physical whole in which the river systems are an interconnected transport system, often working invisibly and in many cases over long time scales. The natural, spontaneous regulation functions are fully dependent on the conservation of the natural dynamics of the floodplains, wetlands and the slopes that contribute water and sediment to the channels. Sustainable development is also related to ensuring balance between today's needs (through the implementation of exploitation functions) and the conservation of the natural regulation functions.

The need to study interactions between land and water and the preservation of the natural functions of ecosystems is very important in studies of wetlands, as described in Hollis et al. (1994) and Carter (1983). Historically, river basin development has implied the drainage and the eradication of wetlands, ignoring the fact that there was a lack of understanding about their function and economic value, in terms of groundwater recharge, flood control, sediment transport and toxicant retention, fisheries and bird life preservation, and waste water treatment. Therefore, it seems logical that integrated catchment management and modelling strategies should make provision for these functions by allowing the correct level of interaction or integration so that processes relevant to wetland preservation are simulated.

In attempting to define and integrate concepts at a physical level, Newson (1997) provides an important contribution by introducing the principle of *land use hydrology* instead of just referring to *hydrology*. The *land use* element indicates a very important role in the hydrological process as the land surface:

- constitutes the interface or major control between the driving forces that operate the system (the climate) and the drainage network,

- influences the percentage of precipitation that infiltrates and this should be examined in light of the importance of the ground water as storage: according to Newson (1997) ground water represents 25% of the water stored inland, rising to about 96% if the water stored in ice caps and glaciers is excluded,

- together land use and land management influences the volume and timing of runoff via the routing of the water over the ground,

- understanding land use helps to expand knowledge of the processes that govern the operation of spontaneous regulation functions.

Geomorphic considerations are also very important to integrated catchment studies. Dunne et al. (1978) place the emphasis on processes associated with the effects of rainfall and runoff on the landscape, considered to be the most important actions that operate on the landscape, even in arid regions. However, the opposite situation can also occur: the geomorphic features of the landscape can condition the hydrological cycle and the spatial occurrence of runoff contributing areas. For example, the presence of a longitudinal and parabolic dune fields in the Northwest Region of the Salado Basin, coupled with regionally flat topography, conditions development of a delicate equilibrium between evaporation, rainfall, phreatic levels and shallow, surface water bodies. When rainfall significantly exceeds evaporation over a prolonged period, the water table emerges at the surface and geomorphic features condition both the spatial distribution of the initial ponding of water on the surface and the subsequent generation of large surface streams.

2.2.4 Integrated Catchment Modelling

A parallel history can be traced between catchment planning and modelling. Different modelling packages were developed to address the requirements and issues of different water related projects, but most of these developments and applications were carried out within single disciplines. Thorough reviews of mathematical models can be found in Singh (1995), Bowles and O'Connell (1991) and, recently, in the report of the Harmon IT project (HR Wallingford, 2002), amongst others. Typical model developments fall into one the following categories:

(i) hydrological models (rainfall-runoff),
(ii) hydraulic (hydrodynamic 1D) models,
(iii) sediment transport,
(iv) water quality, and only more recently, a set of models that cover wider basin issues such as,

(v) atmospheric, ecological and economic models.

These days, the growing need for integrated catchment management initiatives is promoting development of an interdisciplinary and systematic approach to catchment modelling studies, that tries to account for the different disciplines involved in those studies and serves as a link or conveyor belt that will take and process information from various fields and feed back the results for further analysis. Also, in relation to the concept of sustainability, tools have to be capable of supporting assessment of the full complexity of the river basin system both now and into the future.

Through development of integrated catchment initiatives, various authors started to see that the way forward in modelling terms had to be focused on some sort of linkage between tools, leaving behind the isolated, single discipline centred development of models. For example, Gardiner (1994) suggests that, although model evolution is going to be driven by the client's requirements and by computational advances, the new focus on holistic treatment of catchments and their multifunctional issues may stimulate the development of relatively new distributed and linked models, rather than single counterparts. He also warns policy makers, at the time of selecting a model, that what can be provided (for example, by off the shelf and well known modelling packages) can change the perception of their needs. In his work, Gardiner (1994) concludes that the next generation of models should: a) operate at all scales (from local to catchment), b) be simple and have awareness of the uncertainty involved at low costs and, c) become a fundamental part of a management decision–support system. Finally, he highlights that the next generation of models should focus on development of hierarchical and neural models, compatible models and complementary models of different conceptual forms.

The recent review carried out as part of the Harmon IT project (HR Wallingford, 2002) emphasizes the need to develop tools that can integrate all relevant processes and relationships within a basin as part of the understanding required of all possible impacts associated with a given management policy. In this work, two key concepts are presented:

(i) the required understanding and multidisciplinary expertise can only be achieved by coupling (*linking or integrating*) process modules from various disciplines, and

(ii) that these assemblages of models can be integrated into decision-support systems (DSS) to allow these models to be used by water planners and managers.

The use of DSS will facilitate the decision taking process by planners (who are not necessarily very familiar with modelling) at the same time that the development of generic frameworks and architectures for linking tools and processing data would permit the modelling discipline to move away from being tightly linked to existing commercial packages with proprietary structures.

Despite these general and well intentioned initiatives to develop integrated models, still each discipline seems to have its own agenda, driven by the specific requirements (or ambitions) of capturing in ever more mathematical terms the physical processes that take place in the basin. This leads, for instance, to the development of complex, physically-based, distributed hydrological models such as MIKESHE (Refsgaard and Storm, 1995) and SHETRAN (Ewen et al., 1999).

Not only does each discipline have its own agenda, but also planning agencies still do not specify the modelling activity with a sufficient degree of integration and they tend to specify the development of complex and individual counterparts. For example, the Terms of Reference associated with the Río Salado Master Plan (Halcrow, 2000) asked for the provision of three different process models without making specific reference to the need for model integration.

The importance of using mathematical models in an integrated way is long established, based on the need to have a tool to support decisions that encompasses interventions that may involve conflicting objectives. This occurs within a context where economic, social and environmental impacts have to be quantified as much as possible in order to guarantee to stakeholders and prove to regulatory agencies that sustainable actions are being taken on a catchment-wide basis.

2.3 Surface Water and Ground Water Interaction

2.3.1 Background and Physical Context

Simulation of the interaction between surface and subsurface processes is a longstanding issue for hydrologists and model developers. Numerous papers were found in the literature review on this topic that provide a good overview of the wide spectrum of applications that depend on a thorough understanding and representation of groundwater and surface water interaction.

Early developments focused on coupling of groundwater to open channels to investigate response of the former to step changes in river levels or analysis of bank storage effects due to a flood wave passing along a stream (Pinder and Sauer, 1971; Nawalany et al., 1994; Swain and Wexler, 1993; Perkins and Koussis, 1996). A second group of developments aimed at coupling of GW-SW processes to predict more accurately the response of either groundwater or surface water levels to particular interventions (such as drainage, regulation and water abstractions), estimation of stream flows and the initiation and expansion of runoff contributing areas (Beven et al., 1995; Refsgaard et al., 1995; Ewen et al., 1999; Morita and Yen, 2002). For example, Wyness et al. (1994) modified the Stanford Watershed Model and applied it to several chalk aquifers in the UK to investigate the relationship between abstractions, land use changes and river flows. Rodriguez et al. (1994) used a coupled model to analyse irrigation efficiency with water table variation due to a combination of deep percolation of excess irrigation and seepage from rivers. Parkin and Adams (1998) analysed different modelling options to study surface discharge of mine water from an abandoned coalfield in the North East of England and the impact of groundwater abstractions in floodplain corridors.

Wetlands are today widely recognised as a feature of great importance for flood mitigation, water resources and preservation of ecological habitats (Carter, 1983; Hollis and Acreman, 1994; Acreman and Adams, 1998). Mortellaro et al. (1995) define wetlands as "*those areas that are inundated or saturated by surface and groundwater at a frequency and a duration sufficient to support a prevalence of vegetation typically adapted for life in saturated soils*". This definition applies well to some of the features present in the Northwest of the Salado basin. These authors quote four variables related to the analysis of management strategies (commonly groundwater withdrawals) in relation to wetlands: timing, duration and frequency of the stress, and magnitude of the impact on the wetland (i.e. change in water level). Although they say that a quantitative understanding "*can only come from rigorous scientific research and long term environmental monitoring*", it must also be mentioned that modelling can play a key role if it is continuously informed by the results of the research and monitoring. Therefore, the study of wetlands and their management can be thought of as another key application for which the use of a coupled surface and groundwater model is essential.

The literature review accounts for different geographical settings where the interaction between surface water bodies and groundwater can occur. The thorough study carried out by Winter (1995), on analysis of the interaction of lakes and groundwater, uses parameters representative of the physiographic conditions of glacier units. Sacks et al. (1991) studied the seasonal dynamics of interactions between shallow interdunal lakes in the South of Spain, Bradley (1996) studied the transient water table variation in a floodplain wetland in the UK and Shedlock et al. (1993) concluded that multiple groundwater flow systems can influence wetlands located in complex hydrogeological settings like those that occur in depressions within coastal dune landscapes.

One of the largest "regional" wetland environments in the world is the Everglades in the South Florida District of the United States, which are dominated by flat topography, highly permeable sandy soils, high water tables and a dense network of engineered drainage channels. Due to soil permeability and the shallow aquifer conditions, aquifer levels are highly influenced by rainfall, direct evapotranspiration from the saturated zone and seepage to and from the channels. The Everglades area is undergoing a major plan for restoration of natural processes in an attempt to reverse the environmental alterations caused by the excessive drainage of the basin. Therefore, the coupled models developed for the Everglades present an excellent template for the testing and development of coupled models this research project.

Another area that features some similarities to the Everglades is the North West Region of the Río Salado basin (Buenos Aires, Argentina). This setting is characterised by close interaction of a fairly young, shallow groundwater system that underlies a complex dune field and, therefore, water table levels are also directly governed by direct hydrological stresses such as rainfall and evapotranspiration. During periods of intense rainfall, water tables emerge at the surface, causing extensive and prolonged groundwater-induced flooding situations. This region, as a result of its Master Plan, is at the forefront of an intense period of intervention in the form of the construction of drainage channels to mitigate the impact of flooding on farm activities. With the experience of the Everglades as a backdrop, it is vital that a good understanding of the processes occurring in this region, supported by representative hydrological models, are used as part of integrated catchment studies - before deciding on large-scale interventions that could invoke serious, detrimental environmental impacts in the area.

2.3.2 Current Practices to deal with GW-SW interaction

This section presents an overview of different approaches to study the issue of GW-SW interaction in a catchment. Basically, existing approaches can be grouped into two categories:

(i) Analytical: where the solution is obtained by solving simultaneously the mathematical equations that describe movement within each medium (groundwater and surface water) and between them.

(ii) Numerical: where the solution is obtained by applying a numerical approximation (i.e. finite difference of finite element method) to the equations that represent the relevant fluxes associated with the processes.

Although analytical solution of GW-SW interaction is still the subject of research, it can be concluded that it is still far from being the approach adopted to deal efficiently with practical problems involved in catchment planning. Ostfeld and Lansley (1999) present the analytical solution for computing groundwater levels in an aquifer stressed by evaporation and recharge and bounded by two drainage channels. The governing equation to be solved is the Boussinesq equation for a one-dimensional, unconfined, ground water system with fixed boundaries. With linearization in h^2 (Bear, 1979), this becomes a diffusion-type equation that can be solved using Laplace transforms:

$$\left(\frac{K\bar{h}}{Sy}\right)\times\frac{\partial^2 u}{\partial x^2}+2\frac{W\bar{h}}{Sy}=\frac{\partial u}{\partial t}$$

where,

$$u(x,t)=h^2(x,t)$$

Ostfeld and Lansley (1999) solved this equation for the case where water levels in the bounding channels are constant and verified the results using some test cases run using MODFLOW (McDonald and Harbaugh, 1988). Although the solution performs satisfactorily (using an average groundwater depth between the initial and steady state condition), the practical field of application is very limited. In fact, the interaction between GW and SW is solved by imposing a fixed boundary condition and not by solving the actual transient exchange of water between each body. In a later section, when the MODFLOW program is described, it will be seen that there are no clear advantages to using this analytical approach in comparison with the use of a code to solve the groundwater equations with adequate boundary conditions. Furthermore, if it is not possible to simulate the fluctuations in water level in the bounding channels, then a proper water balance in the surface water body cannot be computed and the method would not be applicable in most practical situations, such as land drainage.

Rather than attempting to solve the equations for practical problems, analytical approaches are more valuable when used to draw conclusions in terms of when (and under what conditions), modelling GW-SW interaction becomes important and when the effect would be negligible. In this respect, work by Lal (2001) constitutes a very valuable contribution to understanding the conditions that govern GW-SW interaction. Lal (2001) solved (using Fourier analysis) the equations for open channel flow analytically (neglecting inertia terms) and 2D groundwater flow to derive conclusions directly applicable to the landscape of the South Florida District. There, interaction between the many existing drainage canals, the overlaying aquifer of high conductivity and the thin sediment layer that separates them, is a key mechanism in the water balance of the region. The contribution of Lal (2001) resides in identification of a number of dimensionless parameters that can characterize the dynamic behaviour of the GW-SW interaction. The following parameters were identified: transmissivity ratio (Pr), canal-width parameter (Pb), canal depth parameter (Pd) and sediment resistance parameter (Pm). These parameters are defined as:

$$\mathrm{Pr} = \frac{(Tg / Sc)}{(Tc / n)}\,; \quad Tc = \frac{qo}{Sf}$$

$$Pb = \frac{B}{\Lambda Sc}$$

$$Pd = \frac{ho}{(m+n) Sf \Lambda}$$

$$Pm = \frac{Tm}{\delta fr \Lambda Sc}$$

where,

B = width of a canal (m)

fr = disturbing characteristic frequency of the system

ho = steady state depth in the canal (m)

km = conductivity of the sediment layer (m/s)

m and n = constants used to describe an open channel flow equation

qo = flow per unit width of canal (m^2/s)

Sc = specific storage of the aquifer

Sf = friction slope

Tc = linearized expression for open channel flow resistance (m^2/s)

Tg = transmissivity of the aquifer (m^2/s)

Tm = sediment resistance defined as $Tm = 0.5Bkm$ (m^2/s)

δ = thickness of the sediment layer (m)

Λ = a characteristic length related to the frequency (and period) of the water level disturbance introduced in a canal, defined as $\Lambda = \sqrt{\frac{Tc}{nfr}}$

These four parameters, when adequately combined, can describe the behaviour of small water level disturbances (of a given frequency) in a canal in terms of time and amplitude decay in the surface and groundwater bodies when the interaction between the two is simulated. The solution obtained is valid for large values of Pr (i.e. the aquifer several times less transmissible than the open channel) and a sediment layer of small thickness (δ). Further manipulation of these parameters yields to a single parameter to characterize the stream and aquifer interaction,

$$\chi = \frac{Pb}{\sqrt{\mathrm{Pr}}}\exp\left(-\frac{\sqrt{0.5\,\mathrm{Pr}}}{Pm}\right)$$

When a sediment layer is absent, the above equation becomes $\chi = \frac{Pb}{\sqrt{\Pr}}$. In the work by Lal (2001) several useful conclusions were obtained: For example, for relatively deep and flat canals (Pd > 0.5) the propagation of a disturbance in the canal is unaffected by its interaction with the underlying aquifer provided χ is greater than 10. This implies that the larger the relative difference between the dynamics of the open channel and aquifer systems, the smaller is the impact of interaction between GW and SW in the propagation of disturbances in the canal. This concept, expressed mathematically in terms of the above parameters, implies wide channels, a low storage coefficient for the aquifer and a high resistance in the sediment layer. The latter is further quantified by stating that when the term $\frac{Pm}{\sqrt{0.5\Pr}} < \frac{1}{3}$ then the aquifer and the canal can be considered as hydraulically disconnected due to the insulating effect of the sediment layer.

Another useful contribution to the understanding of GW-SW interaction was provided by the work by Nawalany et al. (1994). As in the work by Lal (2001), analytical developments were used to draw conclusions that contribute to better, more adequate and approximate use of numerical tools. In this case, Nawalany et al. (1994) analysed use of 2D and 3D models to simulate GW-SW interaction. 2D models are based on the assumption that the vertical component of the flow can be neglected, which is reasonable provided that hydraulic gradients are small. However, flow in the vicinity of streams is clearly three-dimensional and, therefore, selection of 2D models must be done with a clear understanding of the associated limitations and drawbacks. It needs to be pointed out that 3D codes like MODFLOW (McDonald and Harbaugh, 1988) are more widely used everyday, even for large regional scale modelling (Halcrow, 1999) and, therefore, 2D models are becoming less popular. However, the discussion is still valid in order to understand the limitations of applying existing formulae (De Vries, 1993 and 1995; Ernst, 1978) that were developed from a cross sectional (2D) representation of the groundwater flow.

Nawalany et al. (1994) presented the results of several exercises carried out after developing the 2D and 3D analytical solutions for a confined aquifer being recharged by a partially penetrating stream. A set of relationships between geometrical and hydraulic parameters were derived as a function of the ratio between the 3D and 2D flows exchanged between the groundwater and surface water bodies. The general conclusion is that the flow obtained with 2D models always tends to overestimate the "exact" flow: This could be attributed to the fact that in the "real" 3D case the same head difference needs to be used to drive the vertical, as well as the horizontal, component of the flow, so increasing the resistance term. The greater the movement of water from the stream to the aquifer (for example, through an increase of the hydraulic conductivity of the aquifer or a reduction of the streambed resistance) would tend to maximise differences between the two approaches. However, an increase in the proportion of flow that penetrates the aquifer through the banks, as opposed to the bed (for example in deeper and narrower channels), would allow users to obtain more approximate results with 2D models. As a final conclusion from this work, it emerges that the use of 3D approaches for quantifying GW-SW interaction is to be preferred whenever 3D models are feasible computationally.

The literature reports a wide number of developments in numerical modelling of GW-SW interaction. Most consist of numerical solutions of the system of equations that govern the flow of water at the surface with those that describe the flow of water in a porous medium, together with an equation that represents the exchange of flow between both media. The developments differ on various issues, such as: degree of approximation to the solution of the open channel and groundwater flow equations, components of the hydrological cycle taken into account and degree of coupling between GW-SW. Furthermore, each development could also be classified in terms of its objective. Models can be grouped within the following categories:

(i) hydrological, basin-scale models that simulate the different components of the hydrological cycle, predominantly driven by the need to generate time series of flow in streams.

(ii) models that calculate 1D flows and levels in open channel systems (predominantly surface water models) with the prime objective of simulating the dynamic routing of a flood wave. Some of these models were either enhanced by addition of a special module to account for the interaction with groundwater bodies, or coupled with existing groundwater packages.

(iii) as above, but groundwater flow models that were either enhanced through the addition of modules to account for the interaction with surface water bodies (streams or lakes) or coupled with existing open channel flow packages.

In the first group of models there have been a large number of developments, starting with the classical hydrological packages, such as the pioneering Stanford Watershed Model IV (Crawford and Linsley, 1966), and ending with to the complex, physically-based models such as MIKE SHE (DHI, 1999) and SHETRAN (Ewen et al., 2000). The second group of models include the set of developments carried out to analyse the impact of the interaction with the underlying groundwater on the routing of a flood wave, such as attenuation due to bank storage effect simulated by Pinder and Sauer (1971). Finally, the third group encompasses various developments associated with the groundwater flow model MODFLOW (McDonald and Harbaugh, 1988) such as the STREAM package (Prudic, 1989), the diffusive router (Perkins and Koussis, 1996) and the LAKE package (Merrit and Konikov, 2000). There are also a number of developments that coupled existing open channel models with MODFLOW such as MODBRANCH (Swain and Wexler, 1993) and DAFLOW (Jobson and Harbaugh, 1999) that could fall into either the second or the third category.

The following sections provide a description of the key features of each model in terms of its strengths and weaknesses in simulating GW-SW interaction.

2.3.2.1 Hydrological Basin Scale Models

The majority of the hydrological models, used in applications at the basin scale approach GW-SW interaction with a weak (often negligible) degree of coupling between them. Examples of these models are: Stanford Watershed Model IV (Crawford and Linsley, 1966), HYSIM (Manley, 1993), HEC-1 (Feldman, 1995). The key characteristics of these hydrological packages are:

- generally lumped, i.e. they provide a single water balance calculation for each of the sub-basins into which a catchment is subdivided,
- the water balance calculation is based on a "top down approach" in which the movement of water is simulated using a set of vertical storages (i.e. canopy interception, depression storage, unsaturated soil layers and groundwater storage), characterised by their storage capacity. The vertical and horizontal fluxes result from the balance of the inflow to each storage compartment, its capacity and water content for a given time and hydraulic conductivities in each flow direction.
- the movement of water in aquifers is not simulated and water recharging them is generally considered to be lost from the system.
- water entering the soil and overland flow component are usually determined using algebraic infiltration formulae such as Horton, Philips or Green and Ampt.
- most models (i.e. HYSIM, 1993) divide the area below the surface into a set of storages in order to represent more accurately the different responses of the unsaturated and saturated layers of the soil.
- calibration is normally performed by comparing observed and simulated stream flow records and therefore, only an indirect verification is made of the magnitude of the internal vertical fluxes, what cannot be sufficient to argue that the model can represent the response of the catchment (Beven, 1989).
- evapotranspiration is extracted from the different components depending on the availability of water in each of them. However, hydrological models do not generally allow for the abstraction of water

from the groundwater compartments, nor do they allow for any loss to be calculated as a function of varying water table conditions.

- As a consequence of their lumped basis, these hydrological models are unable to represent heads anywhere in the basin and therefore simulate head-dependent physical process using flow-storage relationships.

Figures 2.2 and 2.3 present, as an example, the conceptual representation of the hydrological processes and their linkages simulated in the Stanford Watershed Model IV and in HYSIM, respectively.

As the need for a closer representation of GW-SW processes increased, a number of developments emerged to improve the coupling of these systems. Wyness et al. (1994) describe the work carried out to develop the Integrated Catchment Management Model (ICMM) as a tool to support different management strategies for chalk aquifers in the south of England. ICMM uses a modified version of the Stanford Watershed Model (Crawford and Linsley, 1966) to calculate surface and subsurface processes on a lumped basis. The components of groundwater recharge, overland flow and interflow are generated, with the first being the input to a multi-layer aquifer system that takes into account interaction with open channels. River-aquifer interaction is a feature provided in the model but a single time step is used for both processes and only a water balance calculation is performed in the open channel, so a proper routing of flows is not carried out.

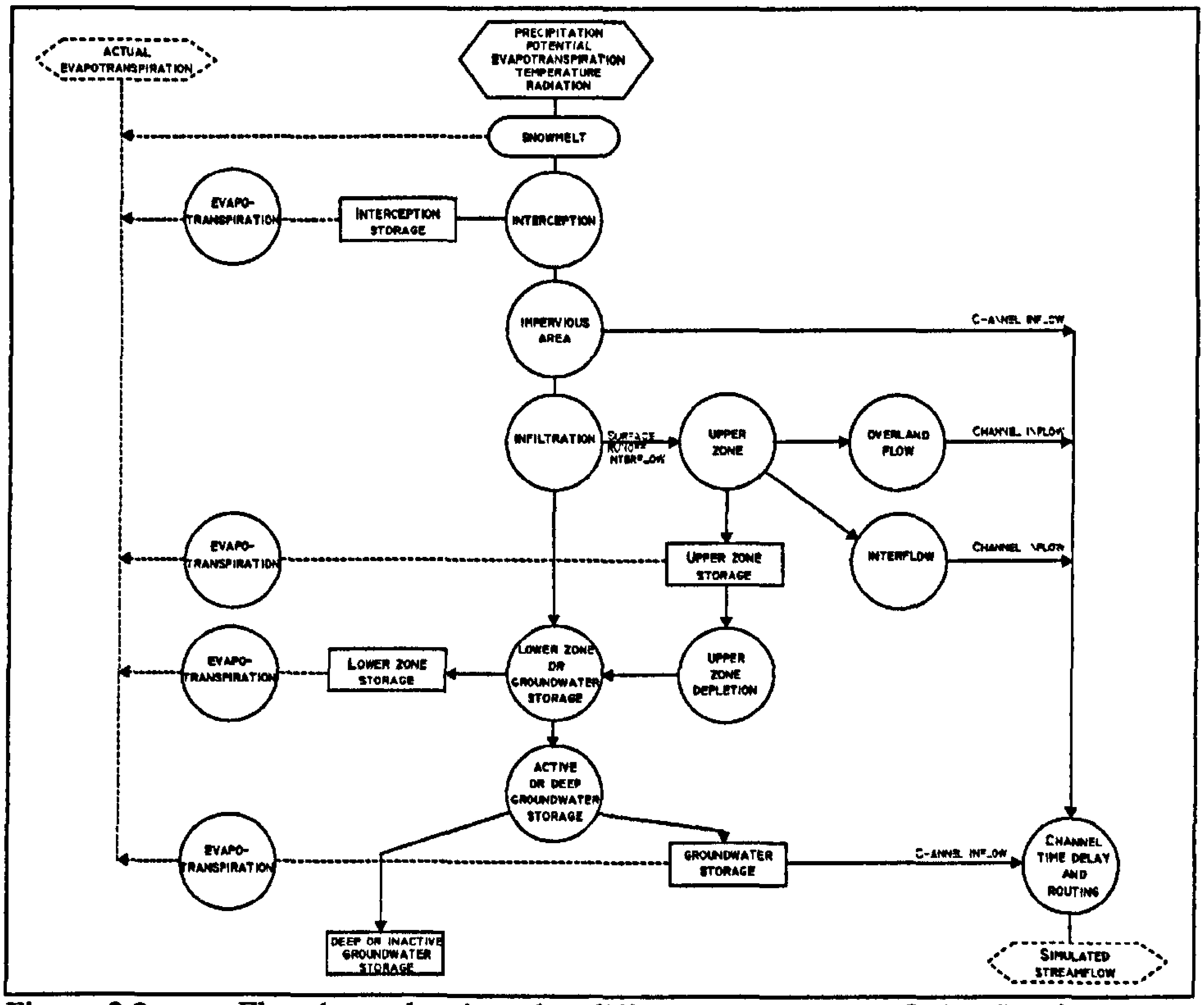


Figure 2.2: Flowchart showing the different component of the Stanford Watershed Model IV. Reproduced from Crawford and Linsley, 1966.

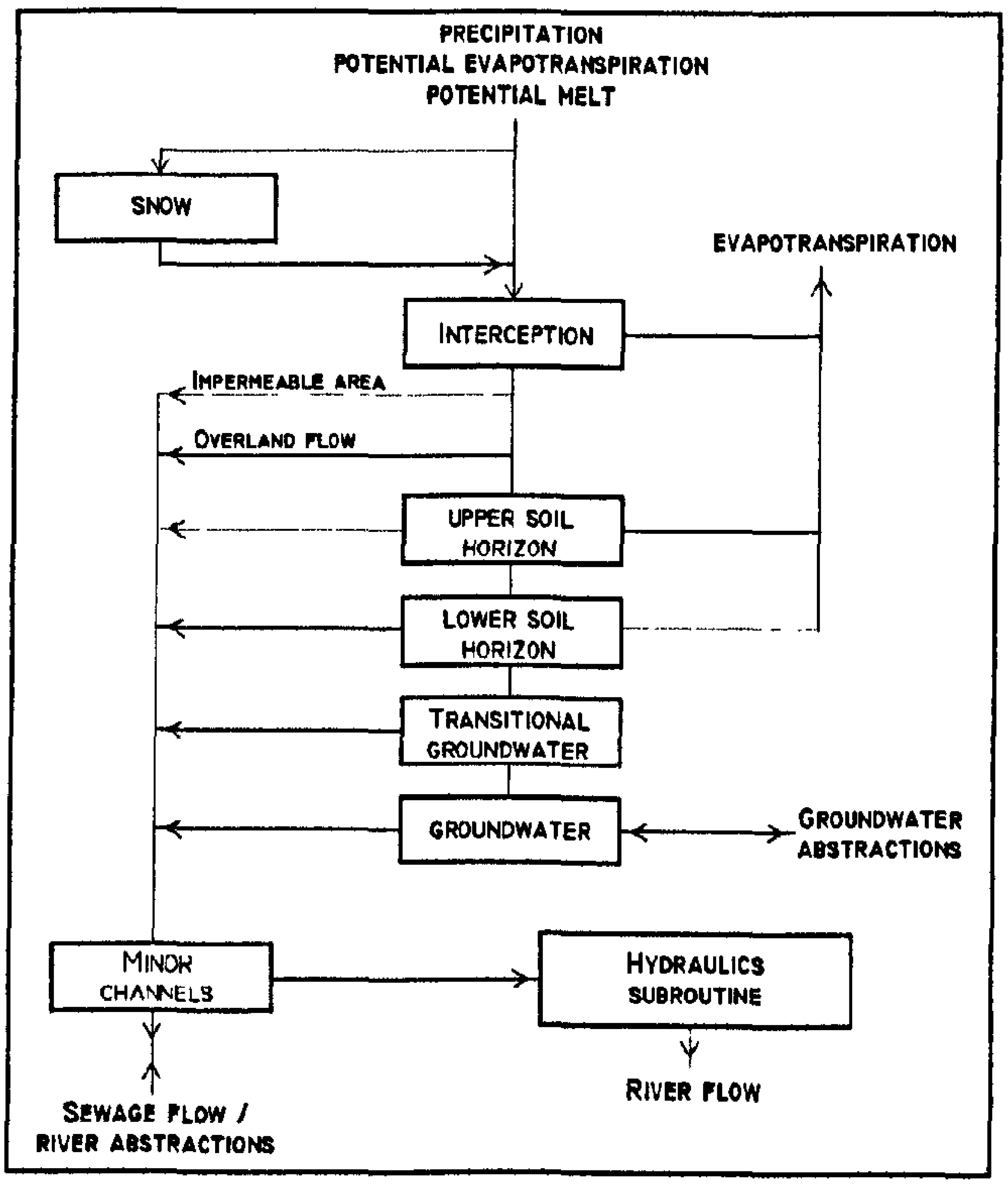


Figure 2.3: Flowchart showing the different component of the HYSIM model. Reproduced from Manley, 1963

Arnold et al. (1993) reported the development of a comprehensive surface and groundwater flow model that consisted of an existing basin-scale surface water model into which a simple groundwater flow and height model was added. SWRRB-Simulator for Water Resources in Rural Basins (Arnold and Williams, 1995) was selected as the surface runoff model. The emphasis in this development was put on adding the simulation of return flow from a shallow aquifer into the total runoff into streams, with the overall objective of predicting the impact of management strategies on water availability for supply. A component to simulate processes in shallow and deep aquifers was added to SWRRB, however both "aquifer layers" are decoupled as the program considers that the water that percolates to the deep aquifer is lost from the system. This development estimates the fluctuation of the water table with time by assuming that the shallow aquifer is recharged from seepage from streams and from the soil profile, using a formula of the type:

$$\frac{dh}{dt} = \frac{Rc - q}{0.8\mu}$$

where,

Rc = recharge to the shallow aquifer,
q = return flow (i.e. the response of the groundwater system to periodic recharge), and
u = specific yield.

However, prediction of water table height is still a lumped estimation that follows the lumped basis of the whole hydrological package. This coupled program is also limited in terms of the time dimension as SWRRB was developed to run on a daily basis and a single time step for the surface and groundwater processes is allowed.

The hydrological package HSPF (Donigian et al, 1995) was coupled to MODFLOW to form an integrated package called ISGW (Davis, 2001), which was claimed by the author to be successfully applied to physical conditions in

South Florida. HSPF calculates surface water infiltration, runoff, evapotranspiration, and surface and unsaturated storages. The deep percolation rate is passed to MODFLOW as recharge, while surface water levels (in rivers and lakes) are also passed to MODFLOW for simulation of the corresponding surface features. MODFLOW then passes to HSPF the calculated leakage between the aquifer and the surface features and the corresponding aquifer heads. The latter is used by HSPF for simulation of the surface water components of the hydrological cycle. In particular, groundwater heads are used to adjust the storage in the unsaturated zone. This development makes an important contribution in terms of the dynamic simulation of the surface water components, such as infiltration, evapotranspiration and runoff, as a function of aquifer heads. This program decouples the shallow and deep aquifers and uses the RIVER package of MODFLOW to calculate leakage using constant water levels previously obtained in HSPF. ISGW runs in a sequential manner until the simulation time has elapsed, making successive calls to HSPF and MODFLOW for every time step. Therefore no iterations are made between the programs within a common time step.

Other developments to simulate GW-SW interaction have followed a more complex route seeking a closer representation of most of the physical processes involved in the hydrological cycle at a basin level. Examples are: SHE (Abbot et al., 1986), MIKE SHE (Refrsgaard and Storm, 1995), SHETRAN (Ewen et al., 1999) and the model developed by Morita and Yen (2002).

MIKESHE is perhaps the most comprehensive, physically-based, distributed model that exists. Recent reviews carried out in order to assess models for the simulation of GW-SW interaction (Camp Dresser & McKee, 2001 and South Florida Water Management District & US Army Corp of Engineers, 2002) ranked MIKESHE very highly in terms of its adequacy for studying management strategies in the complex area of the Everglades.

MIKESHE is, like SHETRAN (Ewen et al., 1999), a further development of the SHE model (Abbot et al., 1986a and 1986b) developed by a European Consortium of three organizations: the Institute of Hydrology (UK), the consulting firm SOGREAH (France) and the Danish Hydraulic Institute (Denmark). Besides the technical aspects of the developments, SHE is a primer in terms of unifying efforts towards the development of a common modelling tool, a concept that was recreated with the work on the Harmon IT project (HR Wallingford, 2002)

The MIKESHE water movement module (WM) simulates the components of the hydrological cycle using six components: interception/evapotranspiration, overland and channel flow, unsaturated zone, saturated zone, snowmelt and river-aquifer interaction. It also performs the simulation of each process using different time steps, according to the characteristics of each process, and allows selection of some of the model components according to a geographical setting and data availability. Figure 2.4 presents the interaction between the different components of the model. The overland flow component routes the excess water accumulated at the surface either from excess rainfall or from flooding induced by a high water table: The 2D horizontal diffusive flow equations are solved for the overland flow while the equivalent 1D equation is used for channel flow. The continuity equation for the channel flow system includes a source/sink term to represent the contribution from overland flow and exchange with the aquifer. Interaction between the aquifer and surface systems (other than the portion occupied by streams) is taken into account as a source/sink term per unit area placed in the continuity equation for overland flow.

Water movement in the unsaturated zone is calculated solving the Richard's vertical 1D flow equation with boundary conditions set at the upper and lower limits of the soil layer. The upper boundary can be either the net rainfall or a water level, when water is standing on the surface: The lower limit is the water table on the saturated porous media. The temporal and spatial variation of aquifer heads in the saturated zone is obtained by solving the equation of groundwater flow in three dimensions.

Calculation of water movement between the aquifer and the river in MIKESHE uses the Darcy equation and takes into account the resistance through the riverbed and the aquifer, as is also used in the lake package of Merrit and Konikov (2000). Floodplain-aquifer interaction is not described explicitly in MIKESHE; although an adequate schematisation can be devised, for example by simulating floodplain flow as a set of parallel, interconnected channels or using the overland flow component. However, the interaction between a single channel section (that includes the floodplain) with multiple aquifer cells is not possible within the current structure of the program.

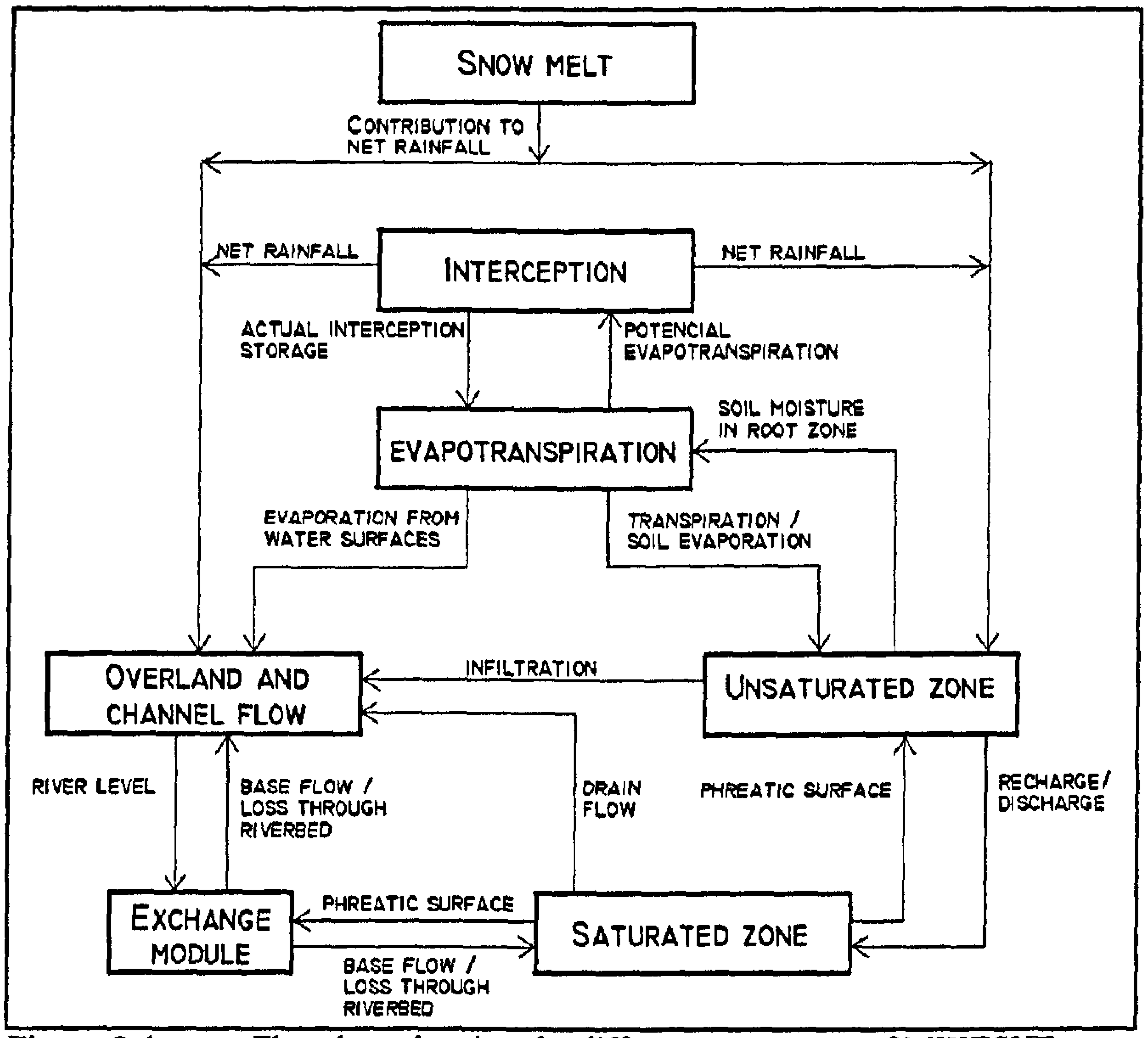


Figure 2.4: Flowchart showing the different component of MIKESHE. Reproduced from Refsgaard and Storm, 1995.

A subsequent version of MIKESHE was developed to couple the watershed part of the model with the 1D hydrodynamic open channel flow model MIKE11. This expands the capabilities of the previous version of MIKESHE in relation to simulation of 1D surface water routing, allowing a full dynamic solution and the inclusion of a wide variety of hydraulic structures. MIKESHE/MIKE11 also enhanced the unsaturated flow component by adding two more options to the user (besides the full solution of the Richard's equation): a simplified version that neglects capillary tension and a wetland module that calculates soil moisture as a linear function of depth to the water table. If the latter option is selected, evapotranspiration is calculated using what is called a "top down approach", which consists of satisfying the potential rate until the capacity of each storage is exhausted (interception, detention storage, unsaturated zone and groundwater). Evapotranspiration ceases if the water levels fall below what is called an extinction depth, an approach similar to the used in the ET package of MODFLOW.

SHETRAN (Ewen et al., 1999) also took a parallel route to MIKESHE, further developing the previous SHE model. In relation to the simulation of the water movement, SHETRAN consists of a 3D surface and subsurface flow and transport finite difference model. The main computational difference between SHETRAN and SHE lies in the way the computational structures are represented. SHE uses a layered approach, solving the equations for the different physical processes in each layer in turn (ground surface, unsaturated zone and saturated zone) and estimating the transfer fluxes between the different layers. SHETRAN basically uses a column approach, able to simulate strong coupling between surface and subsurface processes as the surface forms an integral part of the column. The 3D representation is thus achieved using lateral flow components between each cell of each column; SHETRAN imposes a limitation on the number of lateral connections for each cell.

Along the lines of the MIKESHE and SHETRAN developments, Morita and Yen (2002) reported the results of a thorough review of existing coupled approaches to simulate conjunctive surface and subsurface flows together with the development of a model that couples 2D surface and 3D subsurface flows using infiltration as a time variant internal boundary condition. The development is tested on a hypothetical drainage plot and no results from real project cases were presented. However, their work is very useful to provide insights into the different types of modeling approaches to coupled systems with the emphasis placed on the determination of overland flow initiation and its magnitude as a function of time, rainfall intensity and subsurface soil moisture conditions. Morita and Yen (2002) coupled the 2D non-inertia form (diffusion type) of the Saint Venant equations with the 3D Richard's equations for unsaturated and saturated subsurface flow conditions, using the concept of infiltrability as the interface between the two components and an alternating, iterative solution to resolve the coupling. Morita and Yen reviewed the different types of couplings encountered and grouped them into one of the following categories:

(i) *alternative iterative coupling*: i.e. the equations for each process are solved separately but iteratively at the same time step using a gradient type equation as the internal boundary condition (i.e. Darcy equation). Examples of this type of coupling are the work by Pinder and Sauer (1971) and some 1D models coupled with MODFLOW, like MODBRANCH.

(ii) *external coupling*: i.e. models are executed sequentially for each time step, with information from one used as the boundary condition for the other. Examples of this type are the hydrological packages SHE, MIKESHE and SHETRAN models describe above.

(iii) *external simplified coupling*: in this case, the same philosophy as that described in (ii) applies, but a further simplification is made as the subsurface partial differential equations for the vertical flow through the unsaturated zone are not solved, but only an algebraic infiltration equation is used, such as Horton, Philip or Green and Ampt. This means that the variation with time of the soil moisture conditions in the soil layer is not simulated and therefore the magnitude of the recharge to the aquifer and the overland flow components become decoupled.

Figure 2.5 presents a flow chart that describes the computational sequence used in the development of Morita and Yen (2002). The key concept introduced by this work is use of infiltrability as the time variant coupling parameter that also controls initiation of the overland flow process.

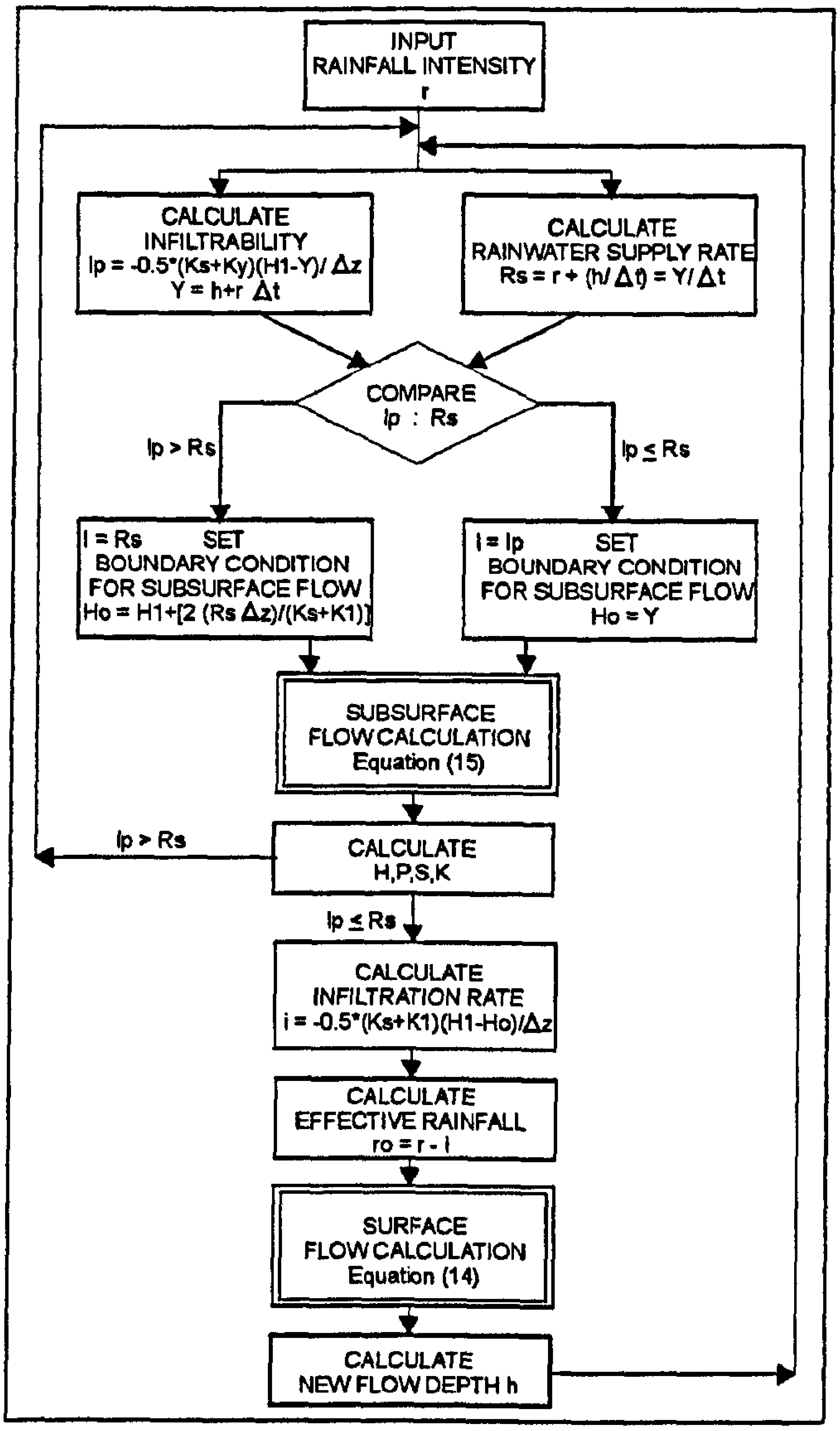


Figure 2.5: Flowchart showing the different component of a conjunctive 2D surface and 3D subsurface model developed by Morita and Yen (2002). Reproduced from Morita and Yen, 2002.

Infiltrability is defined as "*the potential infiltration rate or infiltration capacity under the condition of given surface water depth and soil water content just below the surface*" (Morita and Yen, 2002) and it can be calculated as follows:

$$Ip = -0.5(K_{sz} + K_1)(H_1 - Y)/\Delta z$$

where,

K_{sz} = saturated hydraulic conductivity,

K_l and H_l = hydraulic conductivity and piezometric head in the first node below the surface in the vertical direction,

Δz = thickness of a layer just below the surface where the piezometric head varies linearly with depth.

At every time step, the rainfall rate is compared to the infiltrability to determine the boundary conditions to be used for solution of the 2D surface and 3D subsurface flow equations. This process is repeated until convergence is achieved for the variables of each set of equations. Both types of overland flow can be generated using the infiltrability concept, either the Hortonian case (called "saturation from above") or saturation overland flow that occurs when the top soil layer becomes saturated (called "saturation from below").

An interesting and different approach to those previously described was that adopted in TOPMODEL (Beven et al., 1995). With reference to the high level of physical representation described in the developments reviewed above, Beven et al. start by saying that TOPMODEL "*is not a hydrological modeling package, but rather a set of conceptual tools to reproduce the hydrological behaviour of catchments in a distributed or semi-distributed way, in particular the dynamics of surface and subsurface contributing areas*". The authors reinforce the contrast with classical hydrological packages by saying that TOPMODEL is based on "*some approximate hydrological theory*", recognizing that, due to lack of measurements and the high complexity (and heterogeneity) of surface and subsurface processes, representation of processes must be "*functional while introducing the minimum number of parameters to be calibrated*".

The validity of TOPMODEL rests on the key assumption that the hydraulic gradient of the saturated zone can be approximated by the local surface gradient, $\tan\beta$. Based on this, all the relationships between storage, water table and aquifer contribution to base flow are various functions of the topographic index ($a/\tan\beta$; where a = contributing area to a given point in the catchment), initially derived by Kirkby (1985), but also a subject of research by various authors including: Dunne et al. (1975), O'Loughlin (1986), Zevenbergen and Thorne (1986), Beven and Wood (1983) and Montgomery and Dietrich (1989). The topographic index represents the potential of any point to develop saturated conditions, either due to a large contributing area (a) or due to a low slope angle (tanβ). Other assumptions are: development of quasi-steady state conditions in the saturated media, use of an exponential function to simulate the decay in soil transmissivity with depth to the water table and existence of an uniform recharge rate entering the aquifer. The resulting equation that relates storage deficit (or depth to the water table), in a semi-distributed way, as a function of the physical properties of the catchment is given by:

$$\frac{(\bar{S}-S_i)}{m}=\left[\ln\frac{a}{\tan\beta}-\lambda\right]-\left[\ln T_0-\ln T_e\right]$$

with,

$$\lambda=\frac{1}{A}\sum_i \ln\frac{a}{\tan\beta} \quad \text{and} \quad \ln T_e=\frac{1}{A}\sum_i \ln T_0$$

where,

S_i = storage deficit in a point i in the catchment,

$\bar{S}$ = areal average of the storage deficit,

T_0 = transmissivity of the soil under saturated conditions to the surface,

T_e = areal average of T_0,

A = catchment area.

The equation presented above has two direct meanings. The first is that, given a value of $\bar{S}$, the distribution of storage deficits is a function of the spatial distribution of the soil-topographic index $a/T_o\tan\beta$, which implies that every point i that has the same soil-topographic index would respond hydraulically in the same manner: This is what Beven termed "*hydrological similarity*". This saves computational time and effort, as the hydrological computation is not necessarily performed for every grid (as is most finite difference models), but only for those points that have different soil-topographic indices. When the equation is expressed in terms of depth to the water table, it becomes a tool to determine areas of saturated overland flow ($z_i < 0$) and hence, TOPMODEL supports use of the concept of variably contributing areas to surface runoff. Areas suffering water logging (water table at or just below the surface level) can also be determined by setting an appropriate threshold value for z.

TOPMODEL uses a simple management system for surface and subsurface storages and fluxes in the catchment and Beven at al. (1995) describe how the configuration of storages can be modified to suit specific basin features. The program can handle the various storages usually found in hydrological packages, such as: interception, detention storage and unsaturated and saturated zones, and a moisture accounting calculation is performed for each $a/T_o\tan\beta$ class. A "non-active zone" is defined, with moisture available up to field capacity: Drainage to the water table occurs (from the unsaturated-gravity drainage zone) when moisture is in excess of field capacity. A simple relationship is used to calculate the flux to the water table (q_v):

$$q_v = \frac{S_{uz}}{S_i t_d}$$

where, S_{uz} = storage in the unsaturated zone (gravity drainage), S_i = local saturated zone deficit (a function of the depth to the water table) and t_d = a time parameter. The output from the saturated zone is integrated over the catchment to estimate the baseflow contribution to a stream. The program calculates a water balance and updates the catchment average storage deficit ($\bar{S}$) by subtracting the unsaturated zone recharge and adding the baseflow at the beginning of each time step. Then the distribution of storage deficits and depth to the water table for every point in the catchment is calculated using the general equation presented above for TOPMODEL.

One of the most complex environments, in terms of GW-SW interaction, can be found in the Everglades in South Florida: The inherent, physical complexity of the system is further complicated by the numerous hydraulic structures (drainage channels, abstraction wells, and regulating structures) built in the area decades ago with the objective of improved drainage and water supply. The South Florida Water Management District (SFWMD) is at present devoted to studying all the technical issues necessary to support the management of the existing system and the implementation of the restoration plan, with the objective of recreating the more natural conditions and ecological functions that prevailed before severe engineering interventions took place in the area. In this context, the need for a comprehensive model to simulate GW-SW interaction is a key tool to support planning activities. The SFWMD developed a large-scale hydrological model known as the South Florida Water Management Model (SFWMM), (McVicar et al., 1983): The analysis of this model is brought to this review given its continuous development and the unique characteristics of the area for which it was developed, which is also a template for the testing and application of most GW and SW models (US Army Corps of Engineers and South Florida Water Management District, 2002).

The key characteristic of the SFWMM is its simplicity in terms of the formulation of the equations used to represent different hydrological processes. Apart for the simulation of 2D groundwater flow, no partial differential equations are solved and most of the processes are worked out using mass balance equations. Using the terminology described in the work by Morita and Yen (2002), the SFWMM falls under the category of those externally coupled models where each process is simulated independently (using a daily time step) and, therefore, no iteration is performed between the surface and subsurface simulations within a time step. Simulation of open channel flow is based on a mass balance equation and therefore flood routing is not performed; the incoming flow to a given reach of channel is translated into depth instantaneously using the channel area. Intermediate, upstream stages in the channel (used for the computation of the interaction with the overland and aquifer modules) are calculated by a linear interpolation with distance, using the downstream stage and a pre-defined head loss for the entire reach. Channel-aquifer interaction is simulated using Darcy's equation in the same way as described in most of the previous developments, with an upper bound in the maximum seepage allowed between the two systems based on the amount needed to reach an equilibrium between the aquifer and channel heads. This is an important concept to be borne in mind when discussing potential instabilities that could occur due to fluctuations of the aquifer head, as a consequence of strong coupling under high streambed conductance. When the water table rises to the surface the soil storage is exhausted, actual infiltration is zero and all the rainfall that has fallen in the day is accumulated as surface storage (through ponding), that is readily available for evaporation, at the full potential rate, and for runoff, as overland flow.

Yan and Smith (1994) took this development further and proposed a model coupling the SWMM (McVicar et al., 1984) and MODFLOW (McDonald and Harbaugh, 1988), which was applied in Dade County in Florida, an area that has the same characteristics as those described in the above paragraphs. The work, reported by Yan and Smith (1994), preserves all the features of the SWMM except that the 2D component for the simulation of the groundwater flow is replaced by MODFLOW, allowing for a 3D representation: This has a direct impact on the possibility of simulating the cone of depression associated with a well field, which was highlighted as a limitation in SWMM by McVicar et al. (1984).

2.3.2.2 Coupled Models using Modules developed for MODFLOW

The developments reviewed in this section are based on the coupling of different modules to the widely used groundwater program MODFLOW (Mc Donald and Harbaugh, 1988). MODFLOW is a finite-difference model that simulates 3D flow through saturated, porous media. The program is structured in a way that several modules are called from a main routine that solves the basic continuity equation for groundwater flow. Each module is designed to perform the calculations inherent to the various processes involved in the hydrological cycle, for example: recharge, evapotranspiration, and the exchange of water with drains, surface water bodies and boreholes. The initial version of MODFLOW handled modeling of GW-SW interaction using the RIVER (Mc Donald and Harbaugh, 1988) and STREAM packages (Prudic, 1989). Both modules use the Darcy equation to simulate seepage between a watercourse and its underlaying aquifer:

$$Q = \frac{KLW}{M}(HS - HGW)$$

where,

Q = flow between both water bodies (L^3T^{-1}),
K = hydraulic conductivity of the streambed (LT^{-1}),
W = width of the stream normal to the surface water flow direction (L),
M = thickness of the streambed (L),
L = length of the stream interacting with a single aquifer cell (L),
HS = water level in the surface water body (L), and
HGW = groundwater head in the aquifer (L).

The gradient (as defined in the Darcy expression) is taken as the quotient of the head difference between the water bodies and the thickness of the streambed, which implies that all head loss is assumed to be concentrated in the bottom of the stream. This also means that the stream conductance ($\frac{KLW}{M}$) lumps the losses through stream banks and through the unsaturated part of the porous media. The latter applies when the groundwater head is below the bed level of the stream; in this case the above formula stands but with HGW being replaced by HG (elevation of the bed of the stream). Ignoring the head loss and also time lags in the unsaturated zone would prevent use of these packages where the thickness of this zone is important: However, this situation does not occur in the case of the simulation of groundwater-induced surface flooding.

The main difference between the RIVER and the STREAM packages lies in the way the water in surface is handled. In the RIVER module, the water level in each stream reach is maintained constant during the entire simulation and, therefore, storage in the surface is not accounted for. This implies that, if the stream recharges the aquifer, it acts as a source of infinite capacity while, if the opposite situation takes place, the water from the aquifer is lost from the system. In the STREAM package, the water level in the surface body is calculated using a resistance equation (i.e. Manning) for the flow that results from balancing the inflow to a given reach and the exchange with the aquifer. Although the STREAM package performs some sort of mass balance, a proper routing of flow is not performed: Instead storage within a reach is not accounted for and the assumption of instantaneous downstream propagation of the flow that enters the modeled area is used for each time step of the simulation. Prudic (1989) argues that this assumption is valid as surface flow is propagated at much faster rate than a perturbation in the aquifer system. However this assumption should be revisited in areas where surface gradients are very flat, a large volume of surface water propagates down the system and the surface water level is not small compared to the thickness of active aquifer.

The modularity of MODFLOW has, since its early appearance, encouraged development of new modules and/or improvement of existing ones, generating newer versions of the program such as MODFLOW-96 (Harbough and McDonald, 1996) and MODFLOW-2000 (Harbaugh et al., 2000). The main modifications made to the program in subsequent versions –in relation to GW-SW interaction- are inclusion of reservoir (Fenske et al., 1996), lake (Merrit and Konikow, 2000) and difussion analogy surface-water flow (Jobson and Harbaugh, 1999) packages.

A more realistic representation of the transient fluctuation of lake levels can be found in the Lake packages (LAK) developed by Merrit and Konikov (2000) and by Cheng and Anderson (1993). Both modules use coupling of an independent water balance equation to calculate the head in the lake within MODFLOW. The lake water balance equation makes use of rainfall, evaporation, surface runoff (overland), inflow and outflow from the lake and seepage rates. Seepage between the surface and the groundwater bodies is based on the Darcy′s equation, as in the earlier developments presented above.

The work by Merrit and Konikov (2000) begins with an interesting review of the characteristics of the existing approaches to modelling GW-SW interaction, in which they highlight that RIVER (this is applicable to the STREAM package too) only calculates leakage through the lakebed, neglecting the horizontal exchange of flow. This originates from the fact that the lake is modeled as a body that lies on top of the top aquifer layer and not as occupying a finite volume embedded in the aquifer. The above assumption is valid provided the aquifer thickness is much greater than the water depth in the lake. This is something that Merrit and Konikov (2000) overcome in their work by defining the lake as a number of inactive grid cells within the overall aquifer grid structure. Cheng and Anderson (1993) partially used this concept by allowing the exchange of flow to take place through the bottom and lateral faces of the lake. Therefore both lake packages calculate conductance in the usual manner as the product of hydraulic conductivity divided by "aquifer" or "lakebed thickness" and multiplied by the area through which flow occurs. Merrit and Konikov (2000) further developed this by adding to the conductance term the resistance of flow through the saturated porous media. This can become important when the interaction occurs in areas where the head loss through the interface between the surface and groundwater media is of the same order of magnitude, as it can be argued, is the case in large parts of the NW area of the Rio Salado basin.

An important aspect of modeling the lake as a finite volume of inactive cells embedded in the aquifer structure is the opportunity to simulate drying and wetting of cells depending on the surface water level. When a lake cell becomes dry, the package automatically converts the cell to active and recharge and evapotranspiration are applied to the new column of aquifer. When the cell is rewetted, the cell becomes again inactive and the above fluxes are replaced by direct rainfall and evaporation. This feature is not present in the package developed by Cheng and Anderson (1993). The extreme situation in the lake package can occur if the groundwater level falls below the elevation of the lowest lake cell, in which case the whole lake becomes dry. Once the groundwater table rises, the lake is rewetted using an average groundwater head from previous time steps that is set as the new surface water level. Merrit and Konikov (2000) warn that the retarding effect of the lakebed resistance is not taken into account and that the water budget in the aquifer is not updated with the volume originated by the rewetting exercise. However, it should also be pointed out that a careful selection of time step and grid size is essential to prevent the generation of a large initial volume during rewetting, in particular noting that the average groundwater head used to set a new lake level is not corrected to account for the change in storage between both media.

Modification of a flood wave passing along a stream, due to its interaction with the underlying aquifer, has received much attention and was the subject of numerous developments, one of the most important ones being the work carried out by Pinder and Sauer (1971) to model the effect of bank storage on a flood passing along a river reach. The authors solved numerically the equation of 1D unsteady open channel flow with the 2D horizontal equation for groundwater flow in confined conditions (below the channel) and unconfined elsewhere. Darcy's equation was used to simulate the exchange of flow between the aquifer and the open channel through the wetted perimeter of the latter. The model and results of Pinder and Sauer (1971) have been used for the testing of many subsequent developments.

MODBRANCH (Swain and Wexler, 1993) and DAFLOW (Jobson and Harbaugh, 1999) coupled existing 1D unsteady flow models (BRANCH and DAFLOW) to MODFLOW (McDonald and Harbaugh, 1988). The MODBRANCH approach consists of a modification of MODFLOW to include a modified version of the BRANCH model to control execution of a simulation in relation to the varying time steps in the SW and GW systems. Both packages were modified to account for calculation of leakage and for its subsequent incorporation within the continuity equation for each system. For those cases where coupling is strong and time steps coincide, leakage is calculated separately in each system as an implicit function of the head in the aquifer and in the open channel. When time steps do not coincide, the aquifer head calculated in MODFLOW is passed to BRANCH and an average leakage rate is calculated using varying surface water heads. The resulting leakage volume is passed back to MODFLOW to be taken into account in the continuity equation. Then, successive iterations between both programs take place until the difference between successive heads in the aquifer and in the open channel fall below a specified value. MODBRANCH uses an approach to managing data very similar to that used by the STREAM and RIVER packages of MODFLOW.

Work by Perkins and Koussis (1996) made an important contribution to the spectrum of developments that coupled flood routers with MODFLOW. In this research a diffusive wave router was used to simulate interaction of a flood wave during its propagation along a river that is closely coupled with the underlying aquifer. The key contribution was to investigate the adequacy of the solution obtained (in terms of propagation of a flood wave) under different situations such as: inclusion of variably kinematic and/or diffusion terms in the unsteady open channel flow equation, degree of coupling (measured by the hydraulic conductivity of the streambed) and coordination of time scales used in the simulation of the groundwater and surface water processes. Perkins and Koussis (1996) concluded, amongst other things, that the degree of physical coupling between systems strongly conditions the selection of time steps for the simulation: The more physically coupled is a system, the greater the need to use the same time step to simulate GW-SW processes, leading to the implicit scheme for leakage calculation. As the degree of coupling decreases, a larger time step can be used for the simulation of the GW system (relative to the time step for the open channel) and leakage can be explicitly calculated using aquifer heads interpolated at intermediate time increments: The latter is the approach previously described in MODBRANCH. A strongly coupled system would imply that the heads in the aquifer would respond faster to the stress imposed by leakage coming from the overlaying stream. Use of a large time step in the simulation of the aquifer process would miss the simulation of that effect, tending to under predict groundwater heads and, hence, to overestimate head difference across the streambed. Another conclusion obtained from their work refers to the use of the kinematic and diffusion terms in the momentum equation for open channel flow, proving that the propagation of a flood wave is much more strongly affected by the use of a variable kinematic wave speed than by a variable diffusion term. Also, it was shown that the contribution of the diffusion term (constant or variable) to attenuation of the flood wave is comparable to that produced by bank storage effects. Therefore this further reinforces the concept that, in coupled systems, the use of, at least, a diffusive router should be the choice in favour of the more simplified approach like the one used in STREAM.

An interesting package coupled to MODFLOW is the Wetland Simulation Module developed by Restrepo et al. (1998). This is of direct application to environments dominated by active surface and shallow subsurface interaction as is the case in the Everglades. This work focuses on simulation of water movement through a wetland where surface water flow can occur in the form of overland (sheet) flow through dense vegetation and flow through a network of open channels between the vegetation (slough channels). The Wetland module simulates surface flow, evapotranspiration, surface water abstractions and vertical and horizontal interaction with the underlying aquifer. This module accommodates the simulation of the soil layer (that separates the body of water from the underlying aquifer) in various forms: as part of the surface water layer simulated within the Wetland module, as an independent confined/unconfined layer or as part of the aquifer itself. Integration between surface and groundwater flow is achieved through the conductance terms (Darcy's law) between horizontal and vertical cells of the finite difference representation. The simulation of overland flow uses the 2D diffusive approximation of the combined continuity and momentum equations. Horizontal and vertical conductance terms are formulated in series, depending on the horizontal and vertical schematisation, i.e. whether the soil layer is simulated as part of the surface wetland layer or as part of the underlying aquifer. The block-centred flow package of MODFLOW was modified to allow specification of anisotropy factors on a cell basis (the standard version only allows for the specification of the factor on a layer basis): This is done to simulate uniform flow through the network of slough channels. However, the need to define the size and location of this network acts against a somehow random generation of the preferential flow lines. Also, the use of constant anisotropy factors with time prevents simulation of deep flooding situations in which the split of overland flow in flow through dense vegetation and flow through sloughs would tend to disappear.

2.4 Discussion

Integrated Catchment Management, defined as the design of intervention strategies encompassing and integrating the fields of hydrological, environmental, social and economic sciences, is vital to achieving sustainable solutions on a catchment basis. In this context, it also clear that modelling will be a core part of this process as a tool to support catchment studies and the analysis of the potential impact of resulting intervention measures, for present and future needs and scenarios.

To support the decision-making process concerning interactions and pressures in the water resources of an area, models have to take an integrated and wider view over the entire spectrum of process domains, such as (quoting the Harmon IT project (HR Wallingford, 2002)): soil processes, runoff, groundwater flow, surface water flow, water chemistry, ecological process and economic considerations. Perhaps the most challenging technical aspect is to find ways to deal with the inherent differences of existing (single process) models in terms of time and spatial scales, data requirements, speed of execution and basis for the representation of processes (deterministic, empirical, stochastic). As described by Serageldin and Steer (1995) and also indirectly stated by other authors (Saha and Barrow, 1981, HR Wallingford, 2002), although there is a growing interest in accounting the views of other disciplines, it is economic valuation that remains the "bottle neck" for analysis of options. This implies that a quantitative approach must be sought as much as possible in each discipline or process involved in the basin, backing up the continuous stream of developments of complex, physically-based, distributed models. However, it is important to attach a warning to this statement, remembering the distinction made by Mitchell (1989) in terms of the various categories that are implied within an "integrated" approach. He identifies that these complex developments can fulfil a useful role at an "operational level", but their usefulness at a "strategic" level can be either condemned to failure by program execution times and data requirements, or their applicability can be limited to small scales.

Besides technical aspects related to the simulation of different hydrological processes, the development of integrated modelling approaches opens up other issues. First, very early in the process, Saha and Barrow (1981) noted that, as evaluation techniques and studies are becoming more complex as a result of the need to contemplate all the issues involved (environmental, economic, social and political), they are also becoming "paradoxically" less definitive. This, it can be argued, is also applicable to the modelling discipline, where discussion on the uncertainties and limitations of existing models seems to expand as new developments emerge. Second, the complexity of the studies being undertaken poses a dilemma in terms of the future need for skills. Development of complex models poses the question of whether the successful development of ICM plans will require distillation of knowledge by a person with a new skill set (i.e. the *river planner*) rather than relying on a team of specialists who will probably tend to view each others issues from their own technical viewpoints. This is also an issue relevant to the topic of modelling and the need for integration. In the Harmon IT project (HW Wallingford, 2002), twenty years after Saha and Barrow's work, a similar question is posed: "*How such modelling systems will be used, remains to be seen, as they will require either a large multi-disciplinary team to support their use, or a distributed team of experts to input specialist knowledge into and extract results from an integrated system*"

Even accepting the need for integration in generic frameworks for Decision Support Systems, each discipline that supports development of single process models will still have their own agenda. For example, debate between hydrologists remains active concerning such topics as: representation of process at the grid level, realism of physically-based distributed models; the possibility of achieving a realistic representation of water movement in the unsaturated zone due to difficulties associated with soil heterogeneity; efficiency in dealing with different temporal scales; representation of all the physical characteristics of wetlands (such as vegetation resistance and resistance of the sediment layer underneath the water body) and; extrapolation of results from the local to regional scales (Beven, 1988, Grayson et al., 1992, O'Connell and Todini, 1995).

Focusing on processes involved in the hydrological cycle, GW-SW interaction is a key process, as it tends to cross a physical barrier often encountered in single process surface watershed hydrological models or groundwater models. Achieving an integrated understanding of the physical processes involved in a catchment requires that GW-SW interaction is understood as this is instrumental to key processes such as: recharge to shallow aquifers; storage for flood mitigation; preservation of aquatic ecosystems; green filtering of water before it is discharged to receiving bodies and; groundwater-induced flooding.

The findings of the literature review carried out on this topic were presented in Section 2.3 and summarised in Table 2.1. Analytical approaches, exist but they are limited to simplified configurations and their usefulness is therefore confined to the research field rather than to application on a catchment and planning basis. There are a vast number of numerical approaches developed to address GW-SW interaction. Some of them are rather hard-wired to specific project and geographical settings (such as the SFWMM – McVicar et al., 1983), while others form part of existing well known modelling packages (such as MIKESHE – Refsgaard et al., 1995).

Key developments for the simulation of GW and SW interaction.	Type of Model	Type of Coupling	Components simulated in each process: Rows: SW Columns: GW	UZ			SZ		
				1D	2D	3D	1D	2D	3D
Pinder and Sauer (1971)	Not specific	iteratively single time step	SV (Darcy)						
River Package – MODFLOW (McDonald and Harbaugh, 1988)	GW model	implicitly within GW flow equations single time step	FHB (Darcy)						
Stream Package – MODFLOW (Prudic, 1989)	GW model	implicitly within GW flow equations single time step	MB (Darcy)						

Table 2.1: Summary Classification of Key Developments for the Simulation of GW and SW Interaction.
[1] In brackets it is included the type of connection between SW and GW.

Key:

FHB fixed head boundary
MB mass balance
DW diffusive wave
SV dynamic wave (full Saint Venant equations)
OVF 2D overland flow
UZ unsaturated zone
SZ saturated zone

Diffusive Router – MODFLOW (Perkins and Koussis, 1996 DAFLOW (Jobson and Harbaugh, 1999)	GW model	iteratively Multiple time steps	DW (Darcy)						
MODBRANCH (Swain and Wexler, 1993)	SW model GW model	iteratively Multiple time steps	SV (Darcy)						
SHE (Abbot et al., 1986)	Hydrological	sequential coupling Single time step	DW (Darcy)						
			OVF (1D Richards)						
MIKESHE (Refsgaard and Storm, 1995) MIKESHE – MIKE11	Hydrological	sequential coupling Single time step	SV (Darcy)						
			OVF (1D Richards)						
SHETRAN (Ewen et al, 1999)	Hydrological – basin scale	sequential coupling Single time step	SV (Darcy)						
			OVF (1D Richards)						
LAK3 (Merrit and Konikow, 2000)	GW model	iteratively Single time step	MB on the lake (Darcy)						
RES1 (Fenske et al., 1996)	GW model	implicitly within GW flow equations single time step	FHB (Darcy)						

Table 2.1: cont.

Wetland Module (Restrepo et al., 1998)	GW model	implicitly within GW flow equations single time step	DW (Darcy) OVF (Darcy)						
ICCM (Wyness et al., 1994)	Hydrological – basin scale GW model	implicitly within GW flow equations single time step	MB (Darcy for river-aquifer interaction and Stanford Watershed Model IV to estimate recharge)						
ISGW (David, 2001)	Hydrological – basin scale GW model	sequential coupling multiple time steps	MB						
TOPMODEL (Beven et al, 1995)	Hydrological – basin scale	sequential coupling single time step	MB (uses infiltration potential to determine inflow to the storage that represents the soil layer)	Mass balance equation applied to areas with hydrological similarity (calculated by the index $a/T_o\tan\beta$). Steady state approximation to the unsteady solution)					
SFWMM (McVicar et al., 1983)	Hydrological and management – basin scale	sequential coupling single time step	MB (Darcy) OVF (Horton type infiltration potential)						
Morita and Yen (2002)	Hydrological – basin scale	iteratively single time step	OVF (infiltrability and 3D Richards for variably saturated flow)						
SWRRB modified (Arnold et al., 1992)	Hydrological – basin scale	sequential single time step	MB (recharge to aquifer calculated from the hydrological SWRRB model based)						

Table 2.1: cont.

In summary, current practice in terms of modelling GW-SW interaction can be categorised into two distinct groups or trends:

- hydrological, basin-scale models (even those that simulate most surface water processes on a physically and distributed basis) have a sequential type of coupling with groundwater models. This means that they are suitable for simulating scenarios where changes in the surface water system occur over a relative long time scales (on the order of days), the prime objective of the model is assessment of a basin water balance and response of the aquifer is not significantly affected by the changes at the surface over a surface time step. This is also strongly dependent on the land surface resistance (and stream and lake bed conductance where applicable) to the vertical exchange of flow with the underlying soil strata.
- There is a growing tendency to develop external modules for the widely used 3D groundwater flow model MODFLOW. All of these developments are focused on simulation of the interaction of aquifers with lakes or streams, although Swain (1994) reports work carried out to manage multiple connections of different types. These surface water modules have a higher degree of coupling in relation to that described for the hydrological models. They allow a more complete simulation of the interaction between a flood wave routed through a channel and the underlying aquifer, while maintaining the capability to handle different temporal scales for both processes through an iterative process. However, these coupled models lack representation of other important surface components such as interception, depression storage, infiltration, evapotranspiration (other than the component over the saturated and lake areas) and 2D overland flow. Examples of these developments are MODBRANCH (Swain and Wexler, 1993), DAFLOW (Jobson and Harbaugh, 1999), the Diffusive Router (Perkins and Koussis, 1996) and the LAKE package (Merrit and Konikov, 2000).

Despite the fact that addition of MIKE11 to MIKESHE would permit simulation of the transit of a flood wave along a stream network, simulation of interaction with the aquifer would still be carried out in a sequential manner and not iteratively (after a solution for heads in both systems is achieved), introducing large errors if the physical coupling is strong (Perkins and Koussis, 1996).

Given the deep penetration of MODFLOW and products with a SHE root amongst modellers, it is anticipated that the two trends of developments will continue for some time. How these developments will merge in the current generation of DSS and generic software architectures is an issue that will have to be addressed and, in this respect, developments associated with MODFLOW have an advantage given the open structure of the program (and modules) and the modular approach that increases the potential for representing different hydrological process.

The degree of coupling affordable in practical terms decreases as the size of the area being studied increases. One of the largest applications encountered in the review pertains to the models developed for the South Florida area (approximately 18,000 km^2), such as the SFWMM. However, this model is one of the simplest in terms of the mathematical formulation of hydrological processes such as open channel flow, infiltration and water movement through the unsaturated zone. The work by Morita and Yen (2002) is perhaps the most detailed development that currently exists in terms of solving iteratively the coupling between 2D overland flow and 3D subsurface process, but it was only tested using experimental field plots.

A feature not encountered in the developments reviewed here is application of coupled models to the simulation of extensive groundwater-induced flooding situations, i.e. those that originate from a regional rise in water table levels to above the ground surface, generating large variably contributing areas to direct runoff. Lumped hydrological models generally fail to simulate the appearance of groundwater on the land surface, as they do not hold any knowledge of the spatial distribution of the catchment features and also, in many cases water recharging the aquifer is considered to be lost from the system without any accounting for storage. Hence, knowledge of the spatial distribution of aquifer heads is impossible.

The conceptual basis of TOPMODEL (Beven et al., 1995) makes this program more suited to the simulation of variably contributing runoff areas. There is an explicit, steady state calculation of the water table position that it is heavily controlled by land surface topography. However, TOPMODEL performs calculations by lumping portions of the catchment that have the same soil-topographic characteristics. Therefore, although the program computes the position of the water table (relative to the ground level), its location in space is not known and the surface flooding distribution would be uncertain. Because the main objective is the determination of stream flows, the total amount of runoff contributing area is what matters, rather than its distribution. This could be modified so that TOPMODEL works on a purely distributed basis rather than in a pseudo-lumped manner, with the calculation of water table performed on a cell basis rather than in the basis of soil-topographic classes. However, the program does not allow for any routing of water on the surface and the instantaneous conversion of runoff contributing areas could over estimate the flows entering the stream.

Combination of the LAKE or WETLAND packages with any dynamic 1D open channel model coupled to MODFLOW could be an alternative approach to simulating groundwater-induced flooding, provided a detailed representation of surface processes such as generalised, 2D overland flow and movement in the unsaturated zone are not needed. This would be the case in low relief environments with shallow groundwater levels, where recharge to the aquifer would be almost a direct relationship with rainfall and evapotranspiration. It would also be applicable to situations where the excess water that appears at the surface follows pre-defined drainage lines that can be adequately modelled by the open channel component.

The suite of models with their roots in the SHE model (Abbot et al., 1986) simulate all of the mechanisms necessary to reproduce groundwater-induced flooding. However, the amount of data required could make the use of this tool for large areas and long terms simulations impractical. Also, for areas where shallow groundwater situations prevail over a thick, unsaturated soil layer, it is arguable whether the modelling of the latter is required with the detail currently included in models like SHETRAN (Ewen et al., 1999) and MIKESHE (Refsgaard et al, 1995).

2.5 Summary

The ultimate purpose of the literature review must be a final statement on the current status of the hydrological science and practice in relation to the key topics identified as being necessary to support this thesis. Within the context of this research, the literature review provided confirmation of the need to carry out an investigation of suitable approaches to deal with integrated catchment modelling problems that feature GW-SW interaction in the form of groundwater-induced surface flooding over large areas.

Table 2.1 summarises the different tools that deal with GW-SW interaction. From the review it was concluded that there is no clear evidence for the existence of a model that could be considered as the "right" tool to deal with GW-SW interaction over large areas, particularly when the objective is to represent flooding that originates due to a large amount of saturation return flow emerging at the surface.

To build on this conclusion, the models included in Table 2.1 were further scrutinised to determine whether they would or not be suitable to deal with the large-scale groundwater-induced flooding problems. Specific questions raised included:

1 Do the tools have the ability to represent the required **physical processes** involved in large-scale GW-SW flooding problems?

   All the models reviewed include a representation of GW-SW interaction of some kind. However, the key issue is whether the models can represent return flow and the subsequent dynamics of water at the surface. In this respect, the RIVER and STREAM packages of MODFLOW clearly fail to simulate the surface water storage and movement. The lake package (LAK3) correctly simulates the water balance in a body of water interacting with multiple aquifer cells, but this would not be sufficient to simulate the transfer of water between a series of surface features, as would be required in the NW region of the Río Salado basin.

Other more complex models, like those with a SHE root, contain a fuller representation of SW-GW interaction, allowing for the simulation of return flow. However, there is an issue concerning over representation of the physical processes and over parameterization that could be used to attempt to deal with large areas with representation of the physical basis of flooding.

2 Can the models effectively handle **large-scale** problems, or are they limited to small-scale applications?

It was pointed out in previous sections that there is a tendency in the hydrological sciences to develop models with ever fuller representations of physical processes. MIKESHE, SHETRAN and the work done of Morita and Yen (2002) are examples that support this argument. However, this trend increasingly precludes applications to large areas, including long term simulations to support basin-scale planning.

An interesting compromise is found in TOPMODEL, which strikes a balance between consideration of spatial aspects and the representation of processes. TOPMODEL was designed to provide a closer representation of surface runoff and flows in streams by taking into account the dynamic contribution from saturated areas. It would not, however, be entirely adequate to map groundwater-induced surface flooding due to its pseudo-lumping of the surface features.

The SFWMM model was one of the few applications of SW-GW interaction encountered for a large area: the Everglades in South Florida. Groundwater-induced surface flooding can be simulated, but the model cannot properly represent the dynamics of the water on the surface and all it supports is a mass balance calculation between storage nodes on the surface.

The issue of large-scale application of models for basin planning leads to the need to pay close attention to optimising the time steps used to simulate each system, which can, inherently, be very different. Perkins and Koussis (1996) highlighted non-convergency issues that arise if the time steps in explicitly coupled developments are chosen inappropriately. The literature review has not provided sufficient information on how to deal with this issue in large-scale applications, and this is further addressed in Chapter 6, where the development of a new coupled model is described.

3 Do the tools have the ability to represent the required degree of **coupling** between processes?

All the hydrological packages investigated have a sequential type of coupling and, therefore, would be unsuitable for situations in which an iterative approach to deal with a strong coupling between processes is required.

Some of the MODFLOW-based approaches, such as MODBRANCH and the Diffusive Router, allow for iterative coupling between the groundwater and surface water systems, but they are limited in their representation of large-scale surface features. Both models can simulate the routing of water along watercourses, but they will calculate the GW-SW interaction on a single groundwater cell basis and, therefore, would be unable to simulate floodplain-aquifer interaction unless a system of multiple channels is included in the schematisation.

Finally, the review suggests that MODFLOW could be initially tested as a modelling tool to deal with large-scale planning where groundwater is the driving mechanism. However, the review also leads to the conclusion that dealing with substantial return flows over large areas would need further investigation and development, justifying the research topics identified in Chapter 1. Consequently, the subsequent chapters of the thesis describe the work carried out to contribute to our understanding and ability to simulate GW-SW interaction over large areas that are predominantly affected by groundwater-induced surface flooding. This extends to the development of a new model (iSISMOD) that couples the 1D model iSIS Flow (Halcrow and Wallingford, 1995) with MODFLOW. Finally, based on insights gained and conclusions drawn from application of iSISMOD to the regional study of the Rio Salado Basin, a framework for conducting modelling studies is proposed in Chapter 8 to contribute the debate on how integrated catchment management can be put into practice.

- CHAPTER 3 -

THE STUDY BASIN

3.1 Introduction

The Rio Salado IMP study was the springboard for the research and selection of the test area used to conduct the research that is the subject of this thesis. Covering an area of 170,000km^2, the Salado catchment is located entirely within the Buenos Aires Province of Argentina, at a latitude and longitude between 35°S and 38°S and 57°W and 63°W, respectively (Figure 3.1). Buenos Aires is the largest and economically most important province of the country, with the Rio Salado area responsible for 25 to 30% of the national production of grains and meat.

The basin comprises approximately 58 administrative districts but, despite its large area, the population is only 1.3million (INDEC, 1991), representing less than a 10% of the total population of the Province. Although the basin is dominated by farming, most people (nearly 80% of the total) live in small urban centres, and no more than five settlements have more than 50,000 inhabitants.

The most prominent feature of the basin is its lack of relief. Other than the two ranges of hills (Tandilia and Ventania) that reach an elevation of 500m and 1100m above sea level, respectively, the remaining terrain of the basin is below 100m above sea level. Gradients are very low: the western boundary of the Province is separated from the sea by more than 500km but the difference in elevation is only 130m.

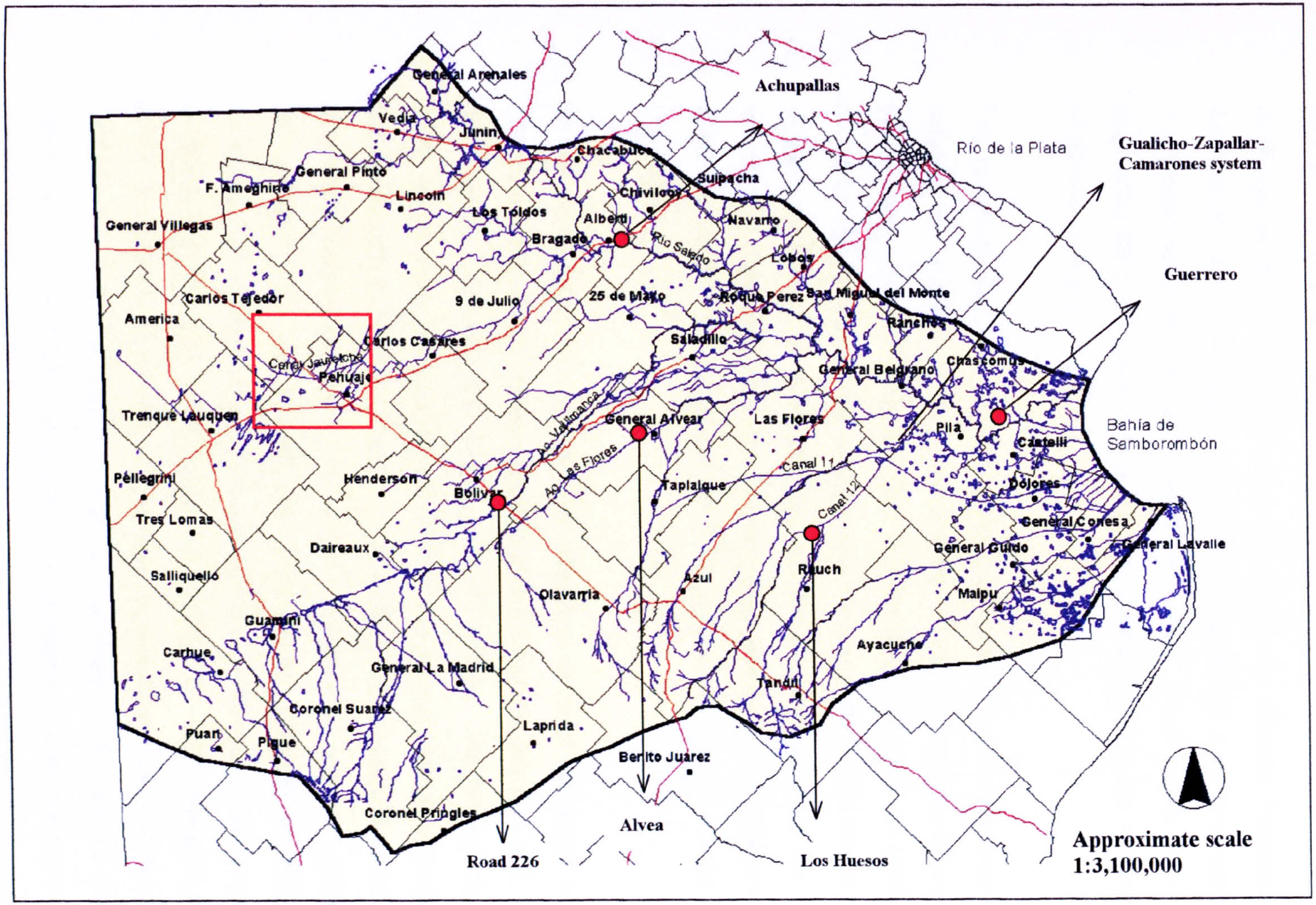


Figure 3.1: Location of the Río Salado Catchment. Buenos Aires. Argentina. (The red circles indicate the location of the key gauging stations)

The Rio Salado crosses the northern part of the basin and discharges into Samborombon Bay after flowing from northwest to southeast for more than 600km. Approximately in the middle of the basin the Rio Salado receives the discharge of its two most important tributaries, the Arroyos Vallimanca and Las Flores. The southern part of the basin is occupied by a series of engineered flood relief channels that run from West to East. These canals drain runoff originating from the Tandilia hills and also discharge it into the southern part of the Samborombon Bay.

The geomorphology and surficial geology of the basin are characterised by the simultaneous presence of landscape elements characteristic of fluvial processes (along some portions of the main river corridors), solution hollows (dolines) in the limestone geology of the north, aeolian deposits (across the whole basin), depressions formed by wind deflation (in the east and south of the basin), alluvial fans (extending from the southern hills), precambrian formations in the south and marine features along the shore land at the eastern margin of the catchment.

The recent history of the Salado basin features a series of sequential wet and dry periods that have affected agricultural and livestock activities and, hence, the economy of the region. During the 20th century, and particularly since 1970, the area has been heavily affected by wet periods that cause prolonged and extensive flooding throughout the region. Flooding attracted close attention from both National and State Governments and research scientists during the 20th century. Also, the Argentinean literature felt attracted by this issue compiling very valuable information and anecdotic evidence on the occurrence of floods and droughts in the region (Ameghino, F., 1886; Moncaut, C.A., 2003). In particular it is worth mentioning the pioneering vision of Ameghino (1886) who clearly manifested against the construction of extensive drainage canals (at the beginning of the past century) prompting for an integrated vision and solution that took into account not only flood problems but also droughts.

The Salado basin has also experienced several major engineering interventions that have had major impacts on its hydrology and which have also affected the nature and geographical extent of its drainage network. At the beginning of the 20th century, major flood relief canals were constructed in the southern part of the basin. These canals today represent a serious barrier to overland runoff that drains northwards from the hills seeking its natural path towards the downstream portion of the Rio Salado. In the 1980s the North West part of the region (which at that time had no natural outlet) was permanently connected to the central part of the Rio Salado by construction of the Jaureche-Mercante-Italia drainage canal (Figure 3.2, B). Finally, in the 1990s, a closed lake system that occupies the southwest corner of the province was linked to the Arroyo Vallimanca (and hence to the Rio Salado) by a canal and a pumping station (Figure 3.2 C). Figure 3.2 shows schematically the changes that have been taking place in the surface water drainage network of the basin through time.

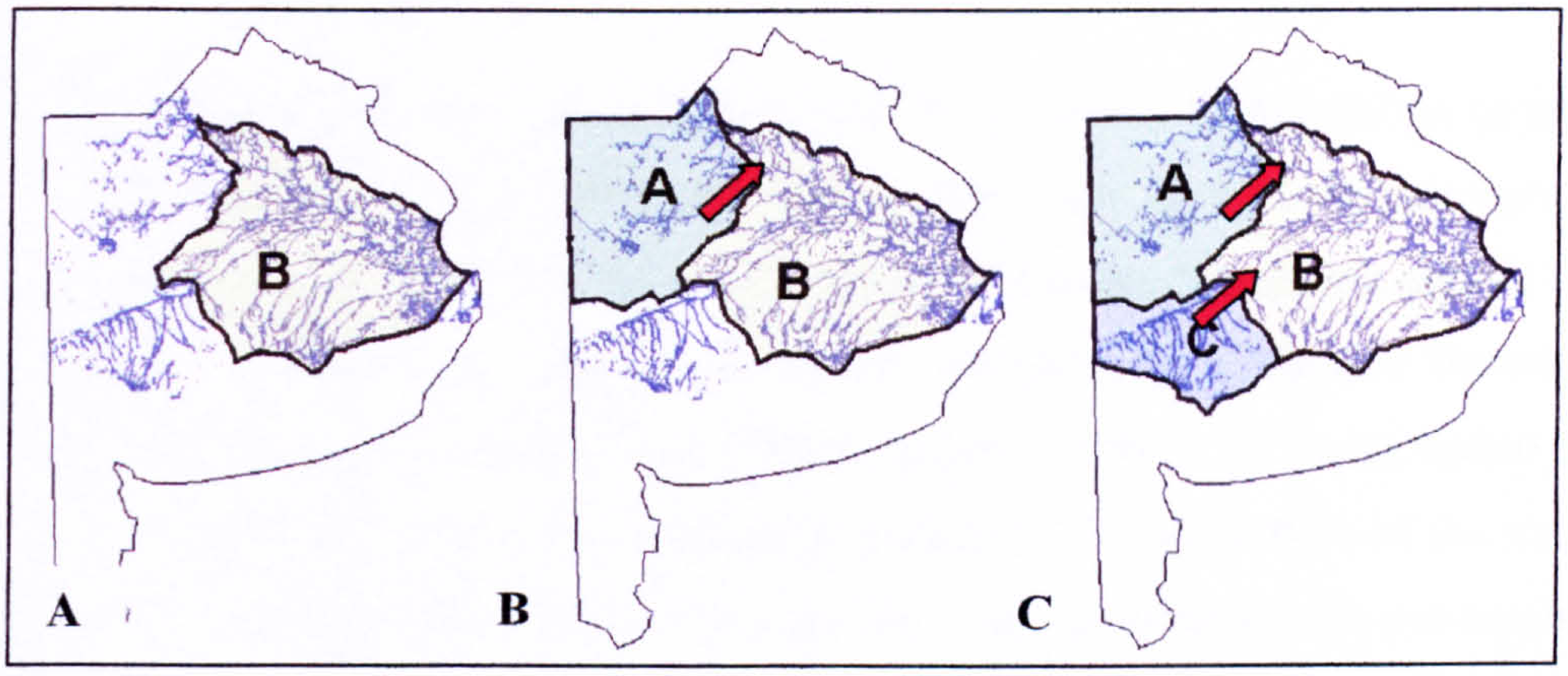


Figure 3.2: Río Salado Catchment. Evolution: from **A** to **C** it is shown how the current Salado basin was formed throughout the years by successive interventions that added sub-regions to the original catchment area (Region B)

In a large area like the Salado basin, where a wide range of geomorphic features are combined with short-term (seasonal) and medium-term climate variability, it is expected to find a degree of natural heterogeneity that could host a wide range of species and habitants. In fact, geomorphic and climatic variability act on the low relief landscape to produce an environment dominated by wetlands, some of which are recognized international (Ramsar, 1971).

It is the association and interaction of all of the above phenomena that makes the Salado Basin a unique geographical setting within which to focus the research activities that are subject of this thesis.

The following sections of this chapter provide descriptions of various aspects of the basin, leading to an understanding of the mechanisms responsible for flooding, which are subsequently addressed in detail in the remainder of the thesis.

3.2 Regional Geographical Setting

3.2.1 Socioeconomic aspects

Although the study area covers over half of the province, its population of just over 1.3 million (Indec, 1991) accounts for less than 11% of the province's total (Figure 3.3). This low figure equates to an average population density of only 7.1 persons/km^2, although there are considerable variations between administrative units, ranging from 0.8persons/km in Pila to 37.3persons/km in Junin (Halcrow, 1999). Urban population accounts for almost 80% of the total but population growth in the area has also been low at around 0.5% per annum between 1947 and 1991.

Among the factors affecting the distribution and growth of population in the area are education, health and rural electrification as it is the provision of these services that affects the quality of life and hence where families choose to live. For this reason, many farm families choose to live in the rural towns, or in Buenos Aires itself, where social services and life opportunities are superior.

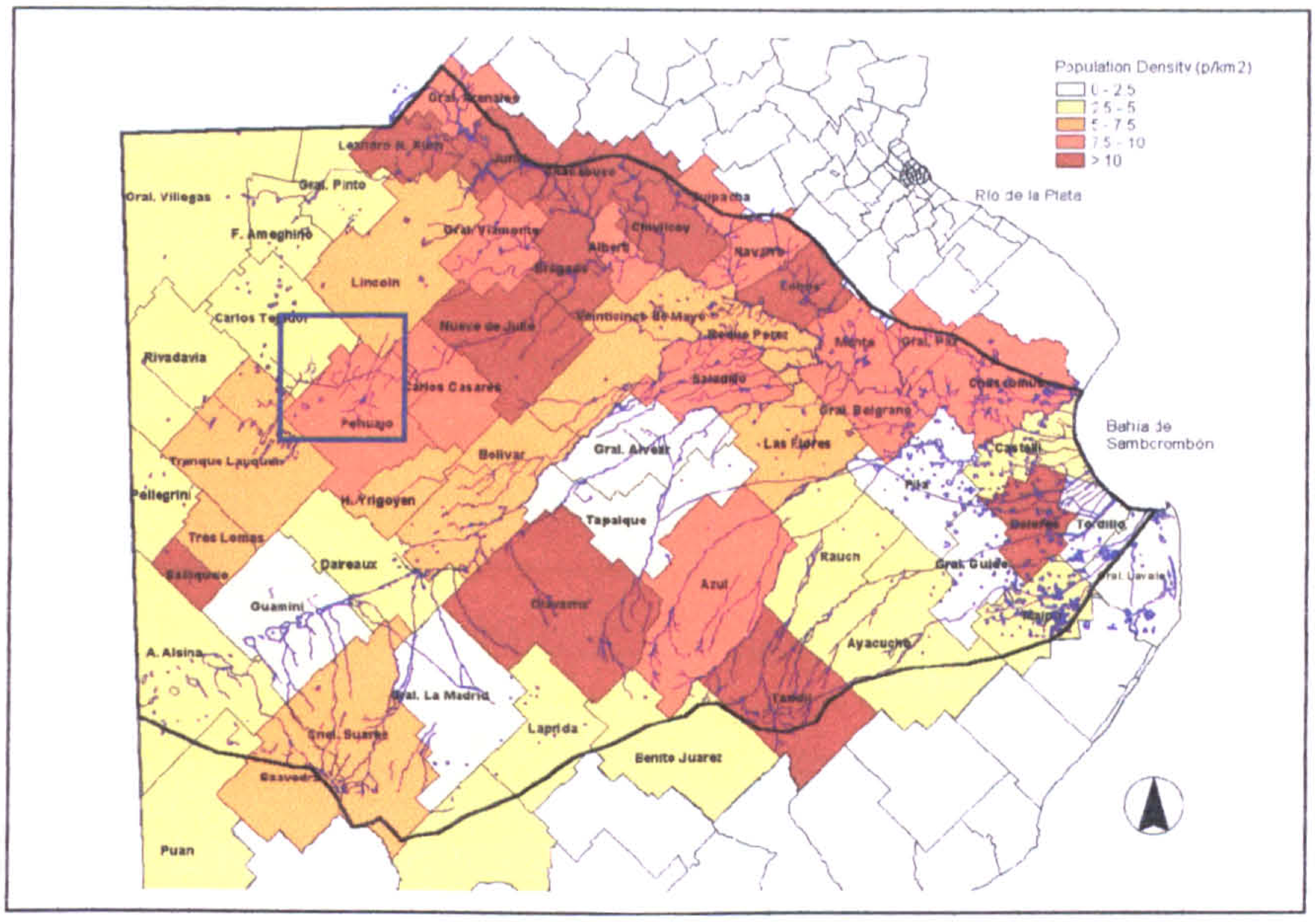


Figure 3.3: Buenos Aires Province and Río Salado Catchment. Distribution of Population.

3.2.2 Hydrometeorology and Climate Variability

The Salado basin can be classified as having a moderate humid and temperate climate, with fairly marked changes throughout the four seasons. The mean annual rainfall for the basin is 855mm (taken over the period 1911 to 1996), with heavy rainfall towards the north of the basin (Figure 3.4). For the purposes of the IMP, which started in 1997, rainfall records up to 1996 were obtained from the Provincial Hydraulic Authorities (DPH) and processed. This rainfall record was made available to the PhD study. It covers both a dry and wet period and it is, therefore, sufficient for the purpose of analyzing different methodological approaches to representing GW- SW interaction.

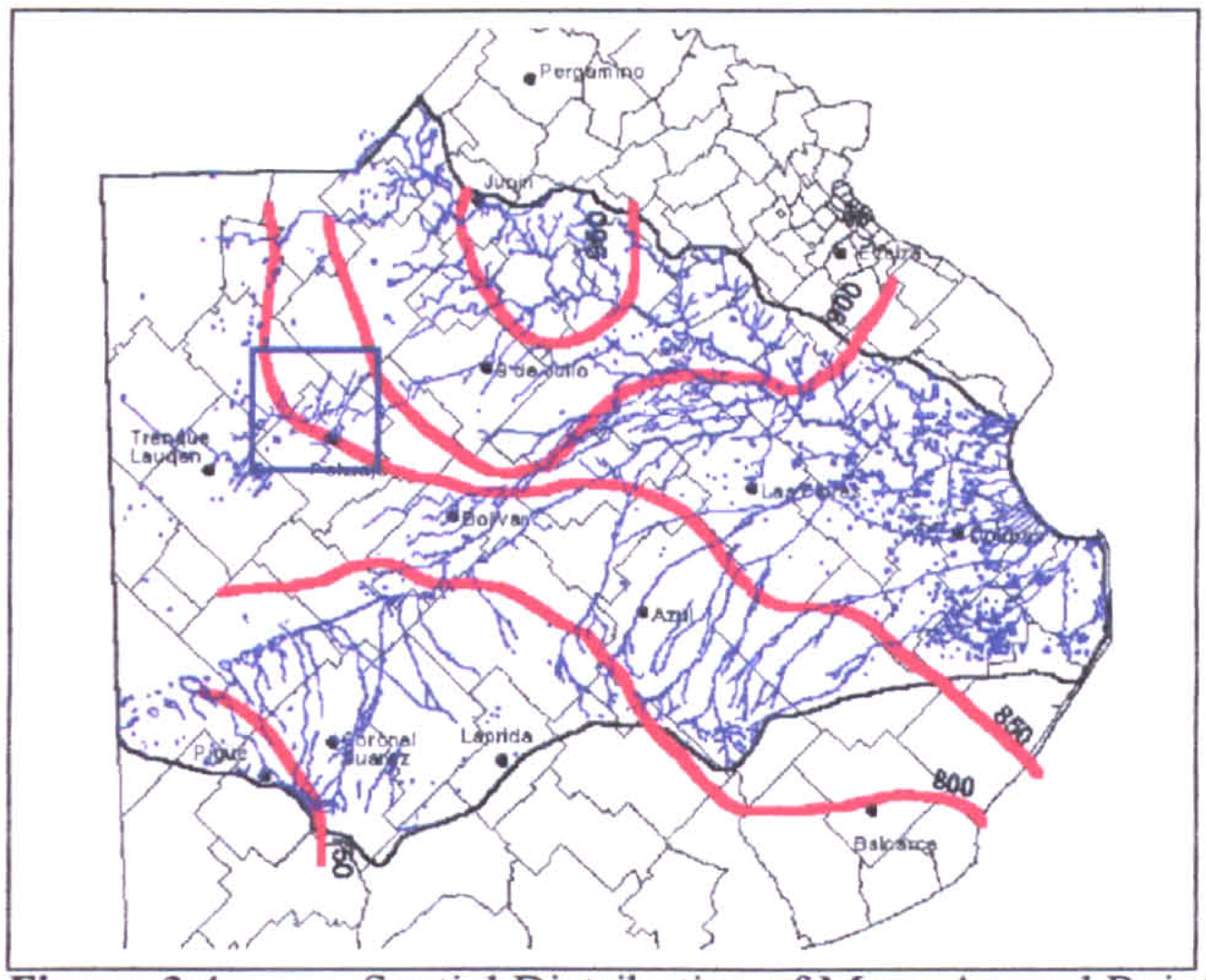


Figure 3.4: Spatial Distribution of Mean Annual Rainfall (mm)

The annual rainfall pattern also shows a marked seasonal variation throughout the basin, with winter rainfall being approximately half of the summer values, and March being a particularly wet month historically. One of the key features of the basin is the increase in rainfall that was detected during the last decades of the twentieth century. This caused important changes to flood frequency in the region and land use practices in the northwest part of the basin. Figure 3.5 shows the variation of the annual rainfall for the period from 1911 until 1996, where it can been seen that, after the decrease shown towards the end of the 1920s, the area is now experiencing a generally rising trend with a starting point at the beginning of the 1960s.

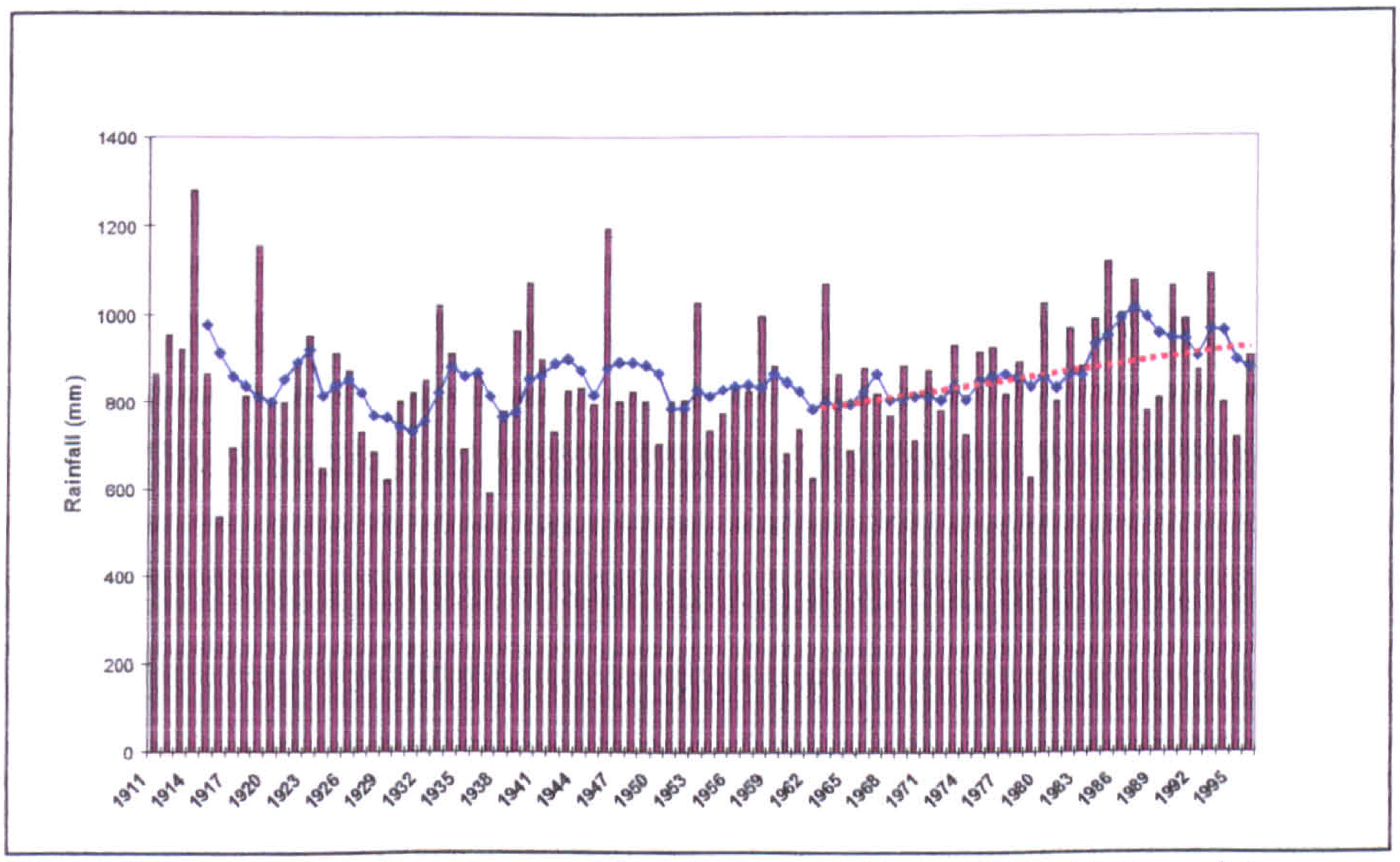


Figure 3.5: Variation of Annual Rainfall in the Basin (1911-1996) and 5-years moving average. Dotted red line indicates approximate trend.

To further illustrate the variation of annual rainfall, Figure 3.6 shows the cumulative deviation from the mean, calculated as follows:

Cum. Dev. (Yr n) = Annual Rainfall (Yr n) – Mean Annual Rainfall + Cum. Dev. (Yr n+1)

Figure 3.6 shows that, for the basin as a whole, annual rainfall was generally lower than the long term mean until the end of 1970s, when a more humid period began with an increase in the annual rainfall to approximately 10% above the mean (930mm in the period 1980-1996 compared to 830mm between 1911-1979). However, despite the general trend, there are also shorter periods when dry and wet years alternate.

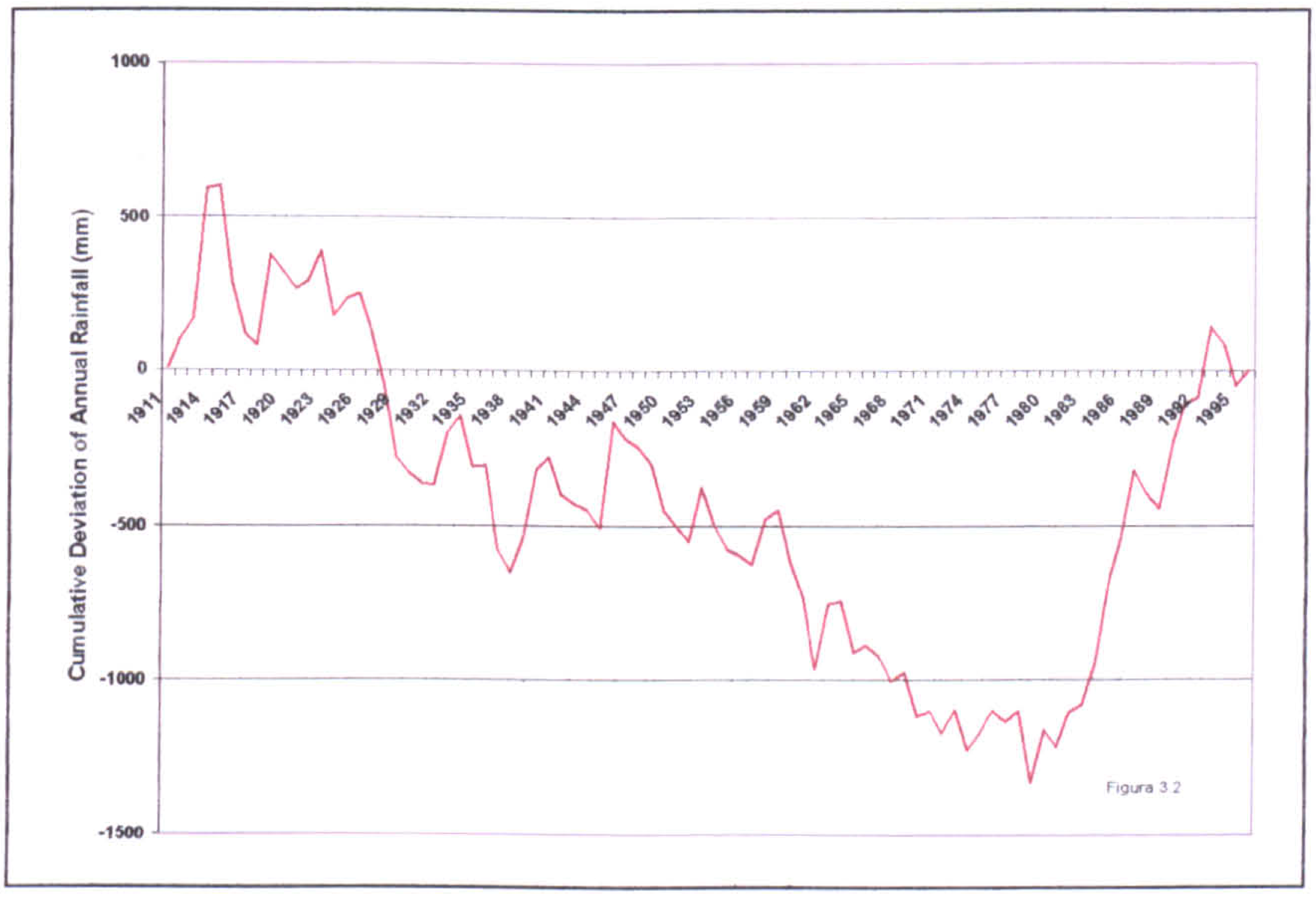


Figure 3.6: Cumulative Deviation of Annual Rainfall from the Mean (1911-1996)

The main annual temperature is approximately 12°C with a marked seasonality throughout the region. Monthly average temperatures vary from 20°C in the summer to 5°C in the winter. Average temperatures do not present significant spatial variation, with only 2°C difference in the average temperature between the northern (warmer) and the southern cooler parts of the basin.

Calculation of the Potential rate of Evapotranspiration (PET) provides useful information on climatic conditions and when analyzed in conjunction with the rainfall also gives a good insight into the potential generation of flooding events. Figure 3.7 shows the spatial variation of PET. It can be seen that there is a marked increased in PET in a northwestly direction due to slightly higher temperatures towards the north and a more marked decrease in relative humidity away from the coast.

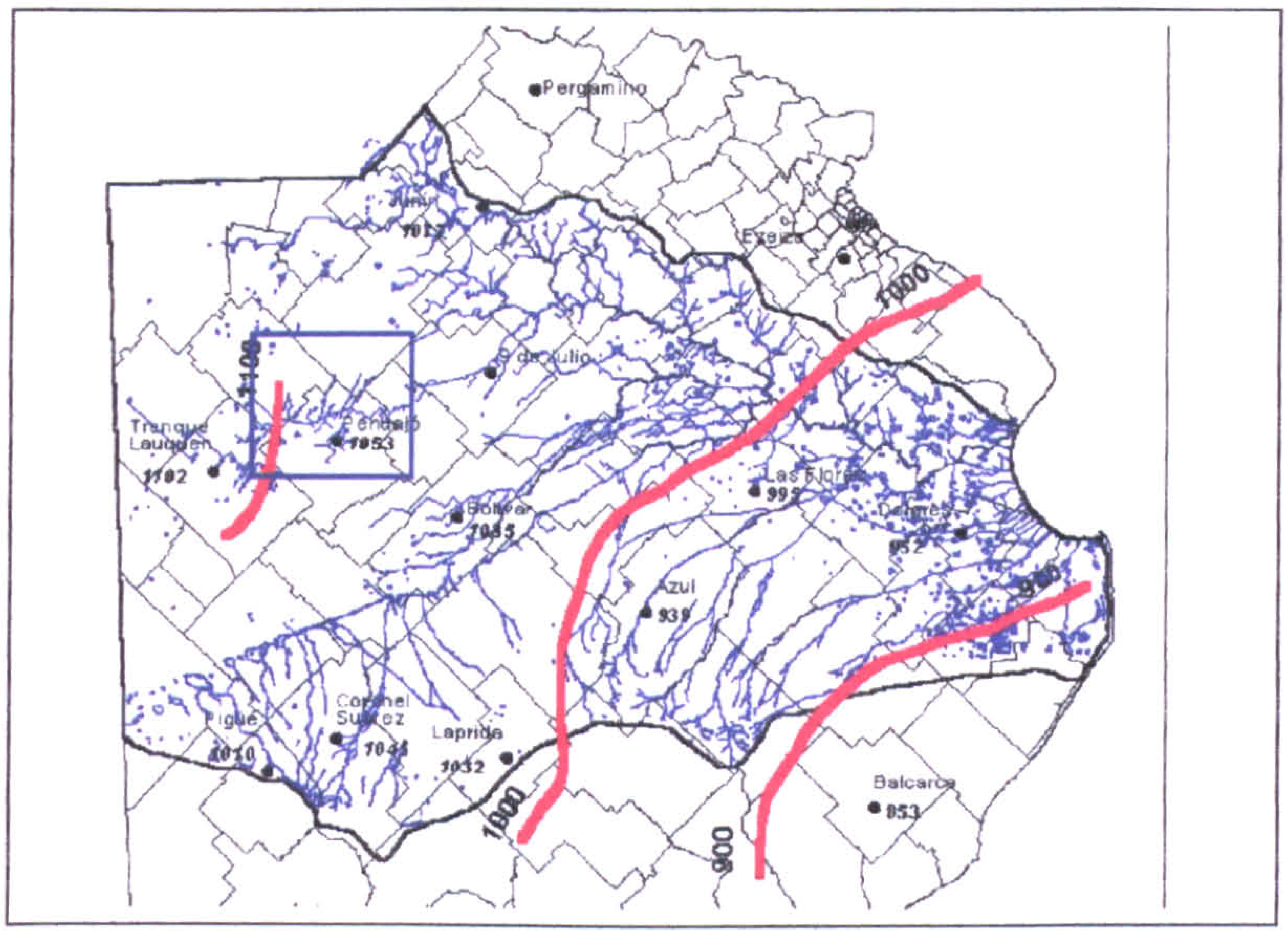


Figure 3.7: Spatial Variation of Mean Annual PET (1959-1995)

Problems of floods and droughts in the region are summarized in Table 3.1 that presents, mostly from anecdotal and historical information, the number of each type of event recorded since the XVI century. An increase in the number of flood events compared to droughts, can be detected, particularly during the twentieth century.

Period	Number of Drought Events	Number of Flood Events
XVI century (incomplete)	1	0
XVII century	2	0
XVIII century	5	1
XIX century	4	14
XX century (until 1992)	6	20
Total	**18**	**36**

Table 3.1: Number of Flood and Drought Events from Historic Records (Halcrow, 1999)

3.2.3 Physical Geography

3.2.3.1 Topography

The characteristic topographic feature of the basin is its lack of relief; other than the two set of hills (Tandilia and Ventania) that reach an elevation of 500m and 1100m above sea level, respectively (Figure 3.8). The rest of the area is a flatland below 100m above sea level with a very gentle slope from West to East. Superimposed on the regional relief there are numerous micro features including small, isolated depressions (deflation hollows) of different sizes, dimensions and degrees of connectivity, and sand dunes that form terrain features up to a maximum height of about 20m.

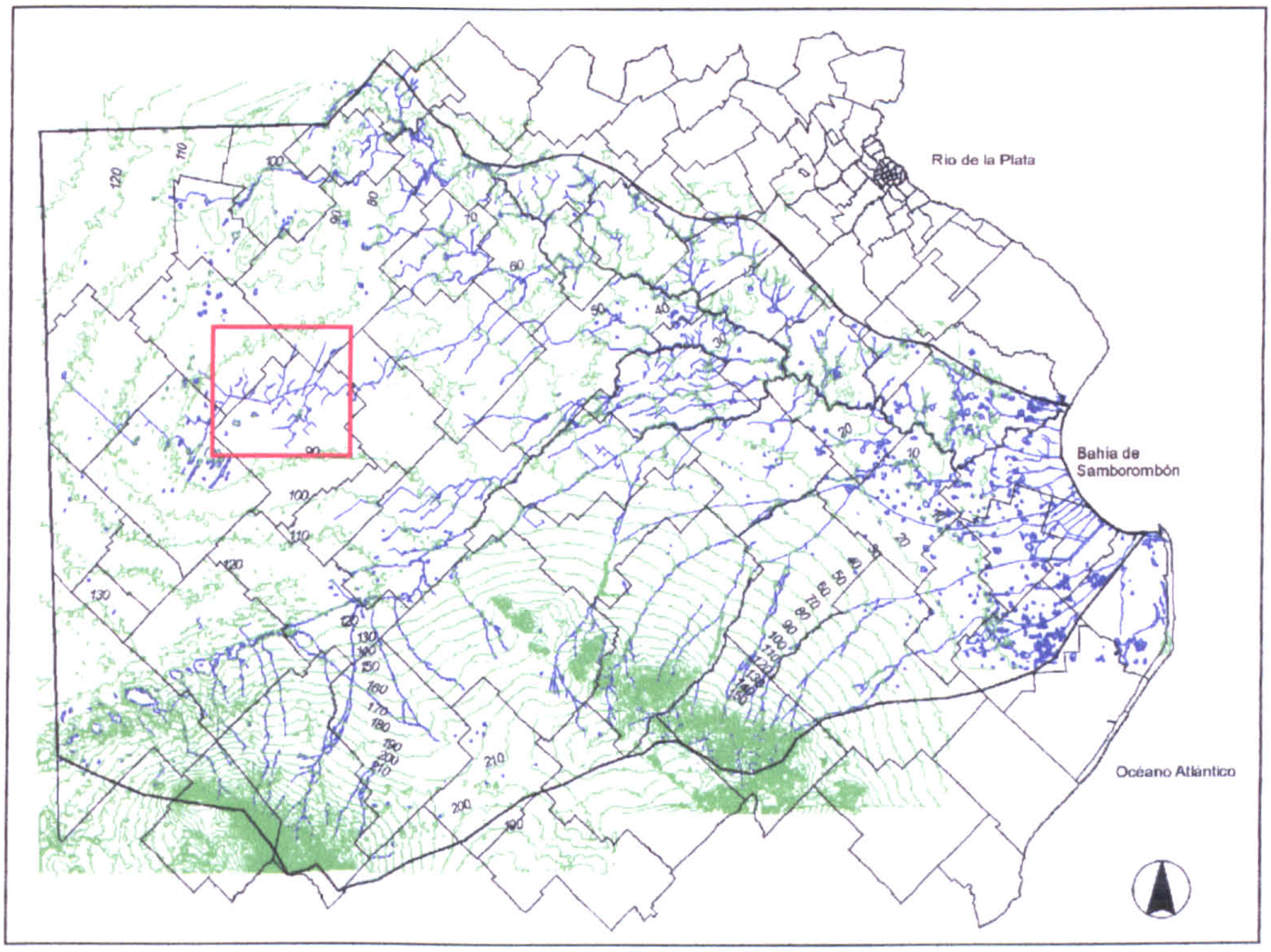


Figure 3.8: Regional Contour Information for the Salado Basin (10m spacing)

3.2.3.2 Geology and Stratigraphy

The regional understanding of the stratigraphy was obtained from a number of publications including those of Yrigoyen (1973), DYMAS (1974), Zambrano (1974), CFI (1980), Fidalgo (1983) and AyEE (1990). Lithological and stratigraphic data are available for deep exploratory boreholes described by Yrigoyen (1973), but otherwise the geological information was fragmentary and dependent upon regional study collations in which a few boreholes drilled for groundwater purposes have been incorporated (i.e. Auge and Hernandez, 1983).

The topographical character of the basin severely restricts the frequency of outcrops revealing any but the uppermost of the geological units, except in the southern mountains where ancient geological units, that have little, or no hydrogeological relevance, are encountered. Unfortunately, there is no systematic recording of the lithologies penetrated by water wells, or correlation with the established stratigraphical units.

The basin is underlain by Precambrian igneous and metamorphic basement rocks, which in turn are variably overlain by Pre-Parana sediments. Some of these units are exposed in the southern mountains. The Parana Formation (El Verde) clays are present throughout the catchment except in the Laprida embayment between the Ventana and Tandil mountains, and along the flanks of those mountains. Overlying the Parana Formation in the northeast are the sands of the Puelche Formation. These are medium to fine grain sands varying in thickness between 25 and 100m. Their southern limit coincides with the Maipu - Junin fault, trending north-westwards, which was influential during Pre-Parana deposition (Yrigoyen, 1973). To the southwest of the fault line, the Puelche Formation is equivalent to the Araucana Formation, with clayed silts sediments (with gypsum) that ranges in thickness from 25 to 100m. On top of the above formations, the Pampeano extends throughout the catchment: In the south, where the Parana and older sediments are absent, it rests directly upon the Precambrian basement rocks. Elsewhere, it overlies the Puelche-Araucana Formations. The basal few metres of the Pampeano unit are argillaceous with the bulk of the unit consisting of clayey and sandy silts (loess) with caliche (calcium carbonate soil horizons). This Formation is reported to reach up to 160m, thinning to the west. Figure 3.9 presents the surface geological characteristics of the Salado basin.

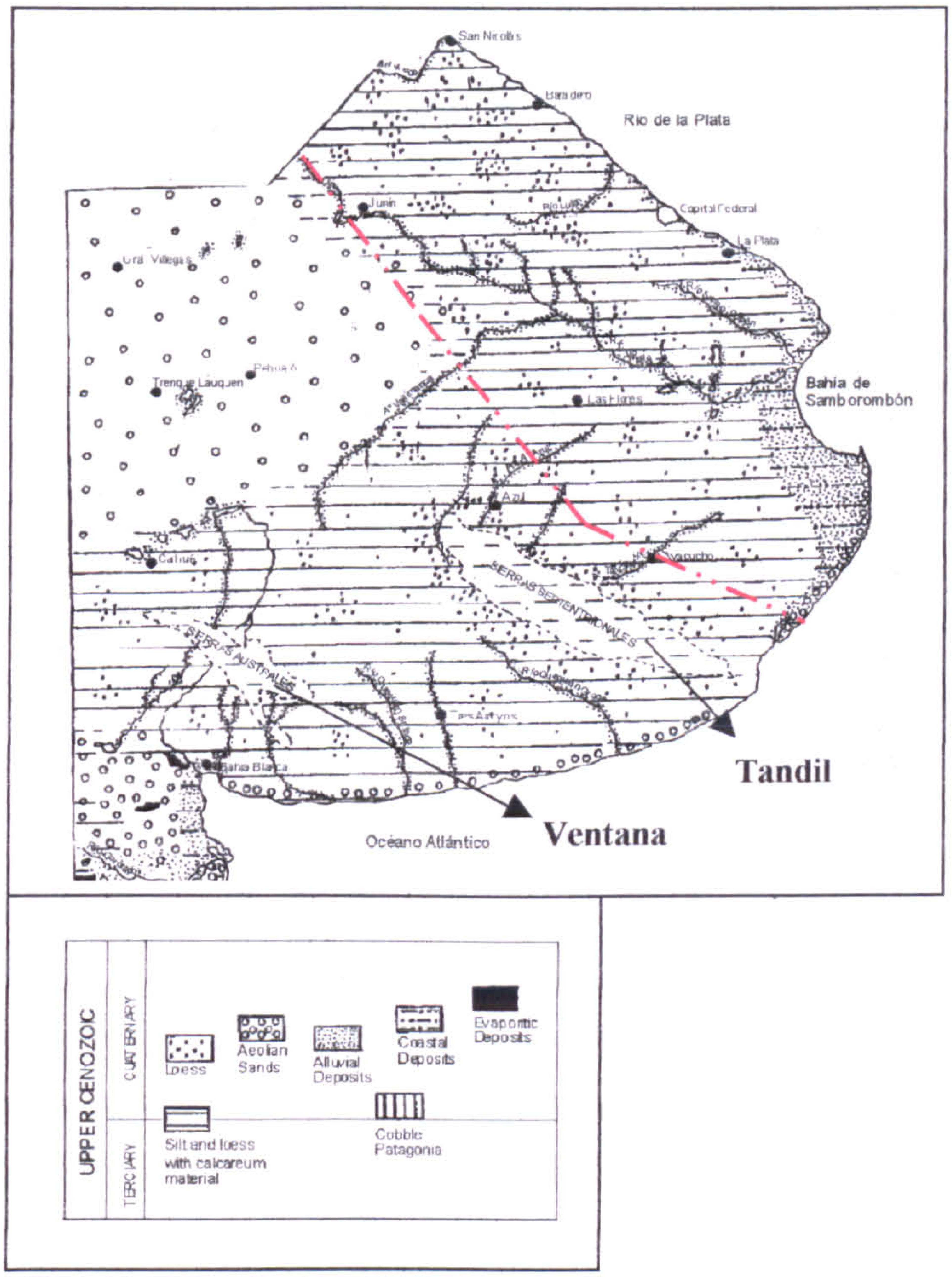


Figure 3.9: Surface Geology. (Auge and De Francesco, 1997)
The red line indicates the approximate alignment of Junín-Maipú fault.

3.2.3.3 Geomorphology

A comprehensive geomorphic study of the basin was carried out as part of the studies for the development of the IMP to establish the origin of the natural forms of the landscape, its current response to rainfall and its possible future evolution under natural conditions or under a developed scenario comprising drainage and flood mitigation works.

Two elements of the study formed the key to the understanding of the natural functioning of the basin and it is important to cover these investigations in the thesis: analysis of the historical origin and evolution of the region and the development of the detailed geomorphic map. The latter led on to a new physical sub-division of the basin that is more consistent with detailed relief features that bear a closer relationship with the geomorphic and hydrological response of the region to hydroclimatic events.

The understanding of the origin of landforms of the Salado basin is a clear example of the need to sometimes look beyond the boundaries of the cachtment as Malagnino (1988) included part of the provinces of San Luis and La Pampa in order to support sound geomorphic interpretation (Figure 3.10). In his work, Malagnino (1988) concluded that the morphological aspects of the Rio Salado are not currently adjusted to current climatic conditions and that the valley currently occupied by the river was formerly occupied by another system that discharged water draining from the Andian glaciars. The under capacity of the system to convey the current runoff generated in the basin was further documented by dominant discharge analysis carried out following the approach first devised by Wolman and Miller (1960). The Figure 3.10 shows the area covered by Malagnino's work.

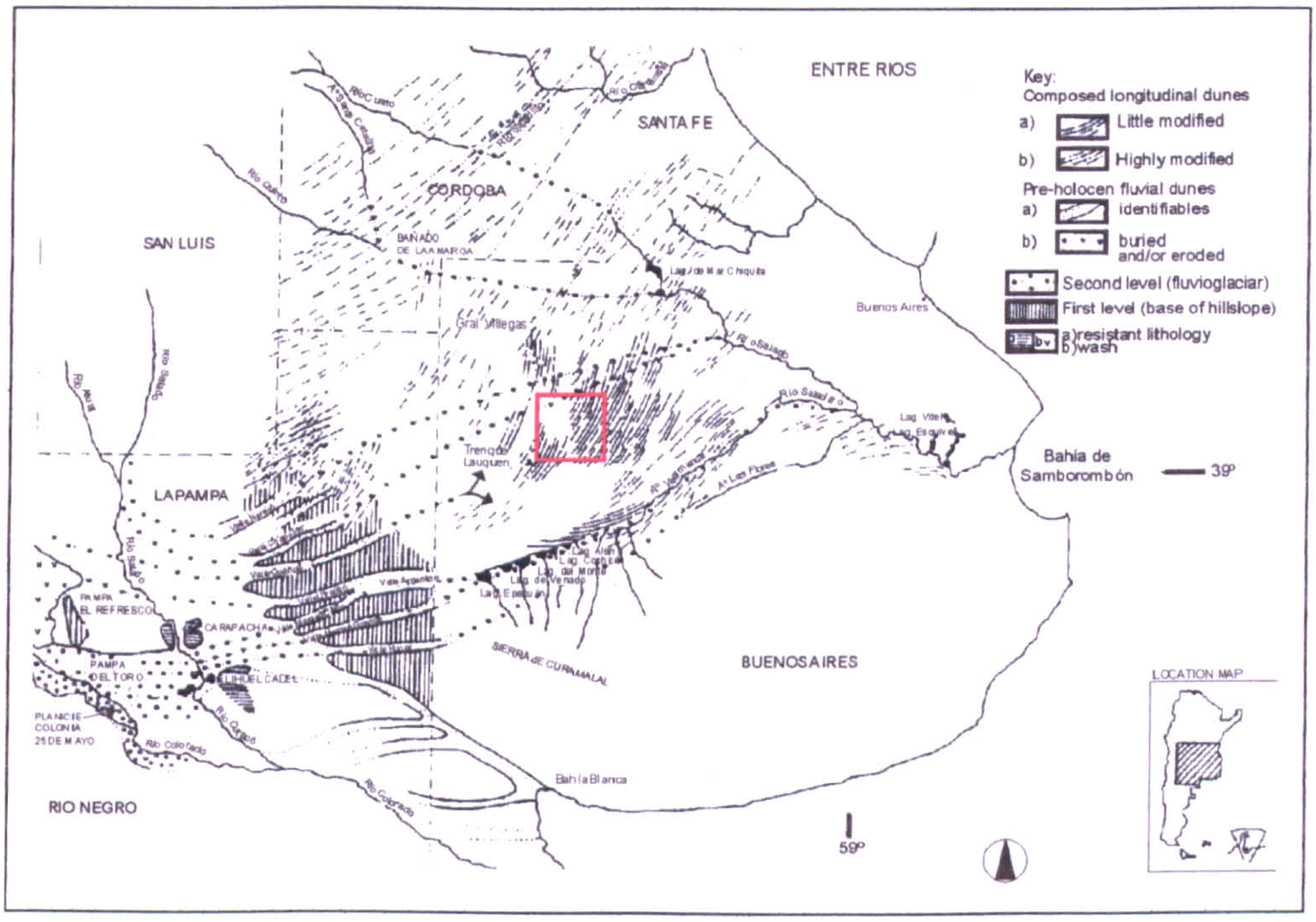


Figure 3.10: Area covered by the geomorphic studies used to interpret the current landform features of the catchment. Source: Malagnino (1988)

An important contribution by Malagnino (1988) was the initial identification of a very extensive field of wind formed, longitudinal dunes located in the Northwest of the province, overlain by another –more recent- field of parabolic dunes (see later in Figure 3.12). The analysis of both dune fields, their orientations and the regional characteristics of the fluvial system, led him to conclude that the dune field was created on top of a pre-existing fluvial system that originated from the northwest (outside the province), and today occupied by the Rio Quinto.

Another important feature of the area, also related to the aeolian mechanism, is the presence of a significant number of deflation hollows created during an arid period, but subsequently covered by water as the climatic condition became more humid. These features show up clearly in the lower part of the Salado River as a continuous series of changes in the top width of the stream.

In relation to the identification of features outside the province, Malagnino (1988) identified (through the inspection of satellite images), a series of elongated depressions in the southwest part of the basin. He interpreted these as ancient fluvial valleys that were once within the Salado basin, but which were covered by the dune fields to the North and buried to the South by alluvian fans descending from the southern hills. These paleo-fluvial troughs provide the fluvial corridors in the basin currently occupied by the Arroyo Vallimanca and Saladillo streams.

It has been proposed that severe climatic changes took place in the region during the late Pleistocene and Holocene eras, and were the drivers for the superposition of the several landforms that overlay the basin. During a first warm and humid period, runoff coming from the west of the country (with its origin in the Andes) eroded deep valleys across the provinces of La Pampa and, to a lesser extent, Buenos Aires. A second and cold period, mainly characterized by a high frequency of flood flows is supposed to have widened those valleys. The third, and the last cold and very arid period deflated the alluvial plains leading to the formation of the dune fields that partially blocked the old river corridors.

The geomorphic reconstruction described above is summarized in Figures 3.11 and 3.12, which show the sub-division of the basin into sub-regions with similar landforms (Table 3.2 describes the key features of each geomorphic subregion), whereas Figure 3.12 presents a sample detailed mapping carried out in the dune field area.

Name of Geomorphic Subregion	**Description**
Upper Salado	The key feature of the subregion is the presence and origin of the Río Salado. The channel of the Upper Salado is smaller than would be expected for its drainage area due to low runoff from Northwest region under the previously dry climate. Bankfull capacity is much less than dominant discharge and so valley flooding is frequent and prolonged.
Lower Salado	In this subregion the key feature is also the Río Salado that in this reach is largely non-alluvial and consists of a series of deflation hollows connected by relatively short alluvial reaches. At the downwind (distal) end of each deflation hollow there is a ridge (dorsal ridge) formed from material eroded from the hollow during the past period when aeolian processes dominated the geomorphology. The channel of the Rio Salado has cut through the ridges to form deep, laterally constrained reaches linking the leveed reaches in the deflation hollows. The constrained reaches have high in-bank flow capacity, but they cannot convey themselves flood flows.
Longitudinal dune field	This subregion presents the largest dune field encountered in the central part of Argentina. Also a key feature is the lack of fluvial features. The entire subregion is dominated by aeolian features which, when subject to flooding processes (large groundwater return flows), give form to large and elongated flooded surfaces. Dunes are generally spaced every 3km to 4km with a length that can reach up to 100km.
Parabolic dune field	This subregion also lacks fluvial features and it is characterized by the presence of parabolic dunes that hold behind seasonal flooded areas fed by groundwater flow.

Table 3.2: Description of geomorphic subregions.

Megaparabolic dune field	In this subregion the field of longitudinal dunes loses its elongated form to become an extensive sand formation lacking an identifiable geometry. This field is cut across by a fluvial system that feeds the right bank of the Río Salado.
Vallimanca	The key feature of the subregion is the presence of the Vallimanca river. This river flows through a complex dune field formed under drier climatic conditions. Aeolian deposition in the valley was funnelled along the axis of the valley. As a result, dune crests form a complex mosaic of ridges and the river channel that has formed due to perennial runoff tends to pick its way between the dunes in an irregular path. The numerous, overlapping parabolic dune crests form a complex terrain, with no continuous floodplain along which flood flows can drain. Consequently, out of bank flows are stored in ponds adjacent to the channel rather than being conveyed along the valley so that flooding is prolonged.
Transition Zone	The longitudinal dunes also extend in to this subregion losing their shape as they get closer to the Río Salado.
Ventana Hillslopes	This subregion is dominated by streams that drain to a set of endorreic lakes (Western lakes) that connect –through a channel- to the Vallimanca river. Their channels are incised into alluvial fans in upper and middle courses, but emerge onto alluvial surfaces between incised reaches.
Inter Hillslope Area	This is a relatively dry region and many streams are ephemeral and/or discontinuous. Perennial watercourses are partially incised into alluvial fans and drain north to the Vallimanca-Las Flores valley.
Tandil Hillslope	Channels in this subregion cross large-ancient alluvial fans before entering the Deprssion subregion. A key feature of this subregion is the presence of engineering works that intercept water flowing along many channels using diversion canals to the sea.
Western Lakes (closed system)	This subregion is formed by a series of interconnected lakes that formed (in the past) a closed system and that is today connected to the arroyo Vallimanca by a canal and a pumping station that operates during flood times.

Table 3.2: cont.

Las Flores	This subregion is characterized by having the Las Flores river flowing through. This river flows along the same valley as the Vallimanca, but its position to the south means that it is outside the zone of continuous cover by aeolian dunes. Hence, its floodplain and channel are more fluvial than aeolian in form. The result is that the floodplain is almost continuous and the channel geometry and dimensions are appropriate to its catchment setting.
Depression	This is a very low-lying area, with very little relief dominated by aeolian dunes. As a result of its terrain and dune morphology, the region naturally has a poorly developed drainage system. Naturally, this region should receive runoff from the Tandilia streams. However, this is now not usually the case because drainage is intercepted by canals and conveyed across the region to the sea with little interaction with the local landscape.
Coastal Zone	In this subregion the fluvial features are just present along the fluvial corridor the Río Salado and the key feature is the presence of marine, inter tidal formations and relict abandoned channels.

Table 3.2: cont.

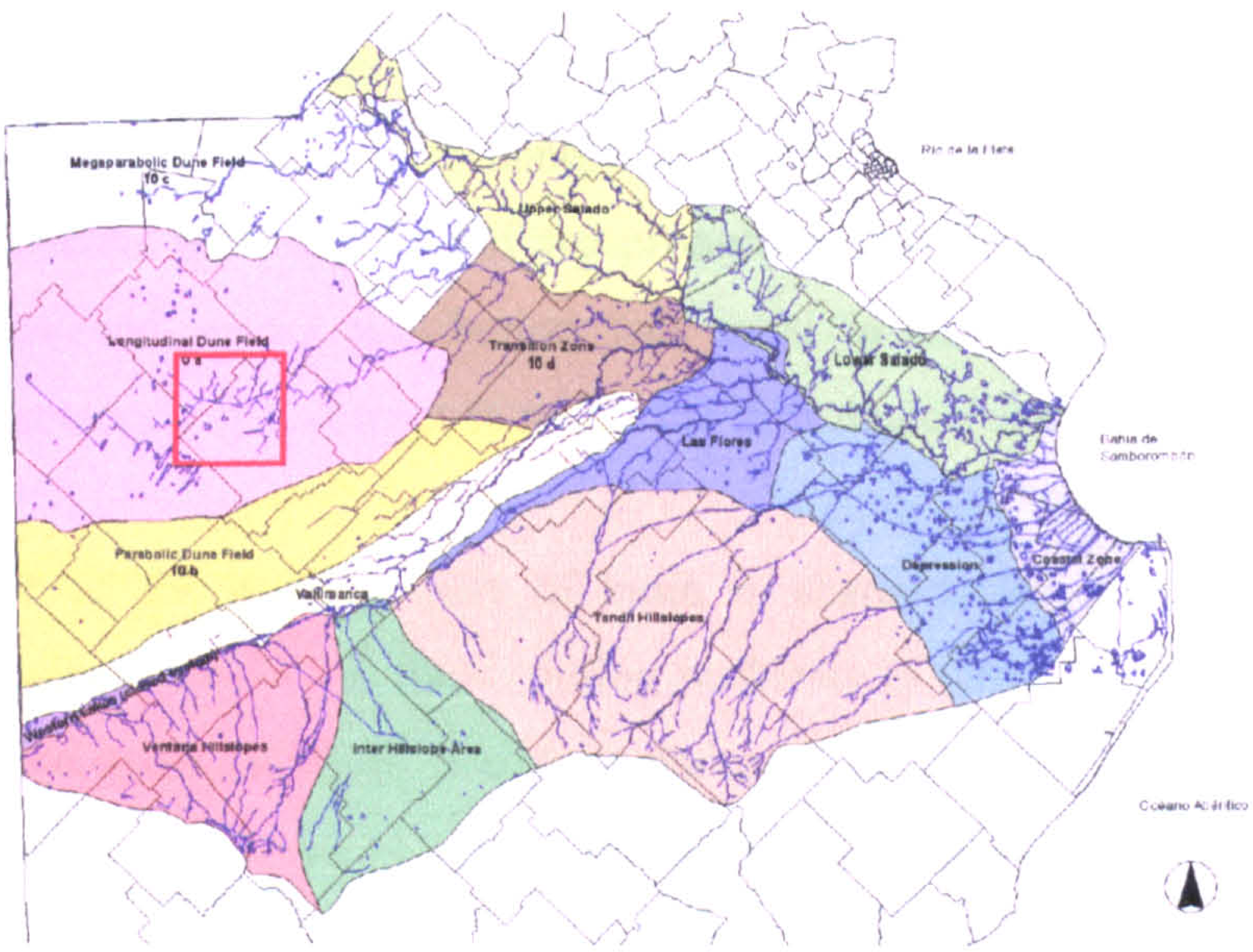


Figure 3.11: Geomorphic Subregions (see Table 3.2 for a description of each subregion)

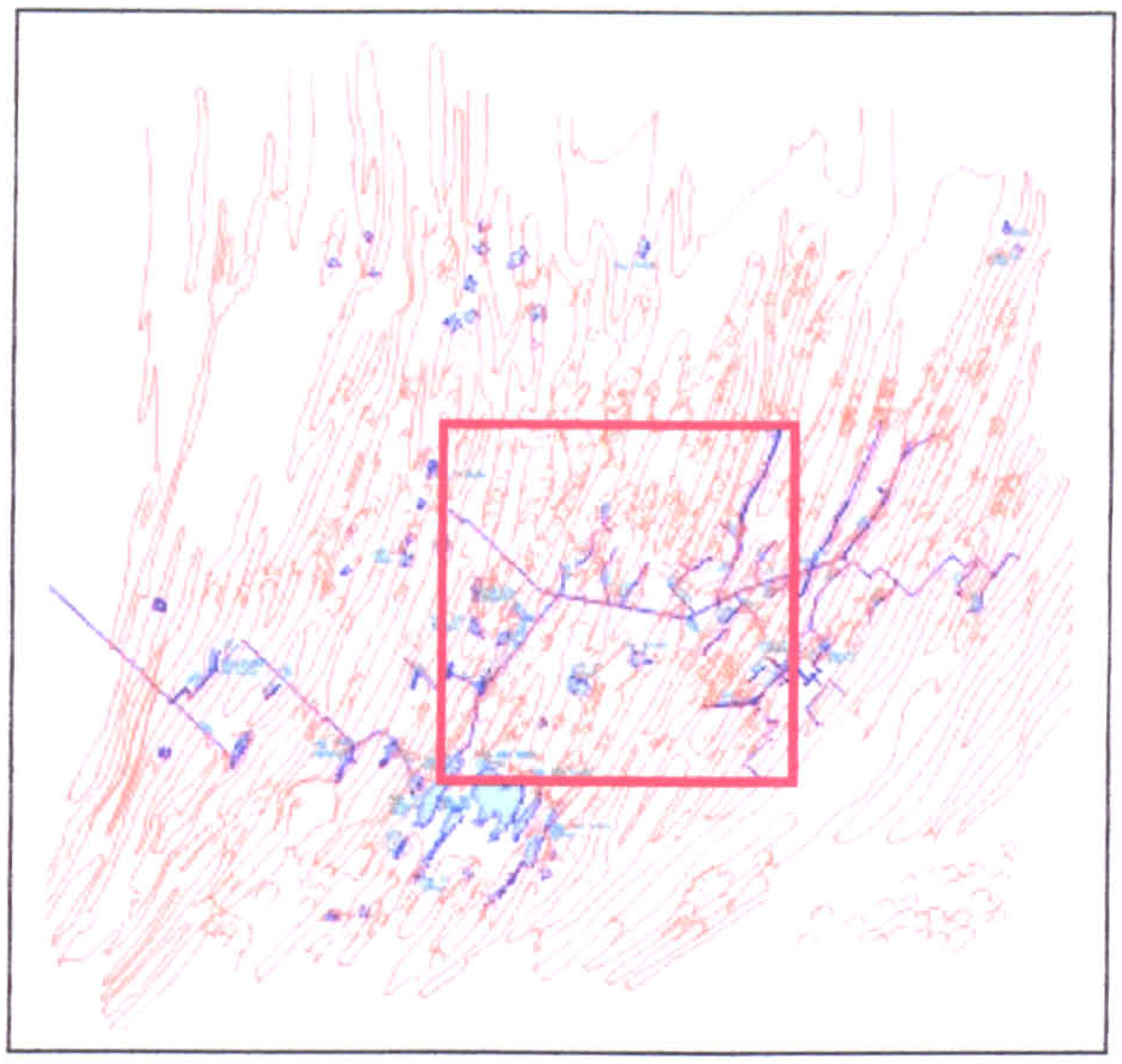


Figure 3.12: Detailed geomorphic mapping in the test area and its vicinities, showing the field of longitudinal and parabolic dunes

3.2.3.4 Soils

Understanding the shallow soil formations in the basin is another key aspect in any integrated study of catchment management, for two reasons. First, the predominent activity of the area is the agriculture and, therefore, a good description of the soil properties (sodicity, alcalinity, texture, drainage) is needed prior to the formulation of a coherent land use and flood risk management strategy. Second, infiltration and unsaturated zone storage parameters are a function of soil properties and, therefore, understanding their values and spatial distribution will assist in the selection of characteristic parameters in any attempt to model the hydrological system.

Most of the northern part of basin is characterized by having sandy clay deposits of up to 2m thick, posing problems in terms of its groundwater and surface water, alcalinity and poor drainage. In the northwest part of the basin there are two type of deposits originating from two sequences of aeolian deposition. The upper layer has a texture defined by the presence of sands and clays with a thickness of 0.5m, whereas the lower layer has a clayed texture. The properties of these types of soil are dominated by low retention of moisture in the root zone due to their fairly coarse textures, and high susceptibility to aeolian and hydraulic erosion.

The central part of the basin (the Zona Deprimida) is dominated by a deep, heterogeneous sediment layer formed by deposits of alluvial material laid down either by out of bank flows in the Rio Salado or overland flow from the slopes of the southern hills. In this area, the hydrological properties of the soils are mainly imposed by high phreatic levels, very frequent water logging situations and high sodicity and alcalinity.

3.2.3.5 Hydrogeology

From the limited hydrochemical information available it was concluded that the presence of poor (brackish-saline) groundwater in the Paraná and older units indicates that the top of the Paraná can be taken as the effective base of any significant groundwater movement.

Away from the coast, the most significant superficial deposits occur within the interfluve between the Rio Salado and the Arroyos Saladillo - Villamanca in the form of hydrogeologically important sand dunes (Malagnino, 1988). Records show that the sands range in thickness from about 30m at the western Provincial boundary to only 5m in the vicinity of Bragado - 25 de Mayo. Elsewhere, superficial deposits, as relevant, are considered as being part of the Pampeano Formation as they are largely derived from that formation and have similar characteristics.

Substantial thicknesses of Pre-Paraná deposits, up to 6km in the northeast, with varying lithologies, occur beneath the catchment, except in the south. Although some of these sediments have porosity, they contain much brackish and saline groundwater, so do not form a significant part of the currently active groundwater system. In groundwater resources terms, the Paraná Formation clays, where present, may be taken as the effective base of the active system. In the south, where the Paraná wedges out, very low porosity Precambrian rocks form the base. The currently active groundwater system consists of the

Araucana, Puelche and Pampeano Formations. The Pampeano Formation forms the top of the aquifer regionally. Locally, sand dunes add to the system thickness. All of the units are in hydraulic continuity and the system may be considered to be regionally unconfined with a free water surface at the upper boundary, although variably distributed confinement and semi-confinement does occur. From a review of the previous studies (DYMAS, 1974; MOSP, 1987; AyEE, 1990) and the lithological characteristics of the aquifer materials, the regional values for hydraulic conductivity (K) and specific yield (S_y) reported in Table 3.3 can be used:

Formation	Hydraulic conductivity K (m/d)	Groundwater Storage Sy (-)
Sand dunes	5-10	0.1-0.15
Pampeano	0.5-5	0.05-0.1
Puelche	10-30	0.1-0.2
Araucana	0.5-5	0.05-0.1

Table 3.3: Hydraulic parameters representative of the formations of the basin.

The combination of stable geological controls and relatively stable sea level following the Paraná deposition gave rise to the low energy deposition sequence now forming the extensive regional plain. The resultant, very small but consistent topographical gradient is reflected in the gentle regional groundwater head gradient beneath the plain, which is the dominant feature of the groundwater head distribution. Regional head distributions were available for 1974 (DYMAS, 1974) for the entire basin and for 1988 for the Northwest (AyEE, 1990). Figure 3.13 shows the latter (in combination with regional groundwater model results), where it can be noted that, in the south, heads in excess of 200m AOD occur bordering the mountains, steep groundwater gradients lead away from these areas but decline towards the plain and, in the west, in the vicinity of the Hinojo - Las Tunas discharge lakes, heads are as low as 79-80m AOD. From approximately the longitude of Carlos Casares to the coast, the head declines from 80 to 0m AOD. Locally, superimposed upon the regional head distribution, there are small (possibly up to 3m) positive head variations that occur beneath the sand dunes. The configuration of groundwater contours shown in Figure 3.13 demonstrates that some groundwater flow occurs to the Rio Salado and to the Arroyos Vallimanca and Saladillo.

Depths to groundwater are small away from the mountains and hills areas, and, historically, depths were greater in the west than the east. However, over recent decades, depths have decreased to less than 5m and are appreciably lower in the east. In consequence, innumerable wetlands and lakes occur, which for most parts of the basin are the surface expression of the water table.

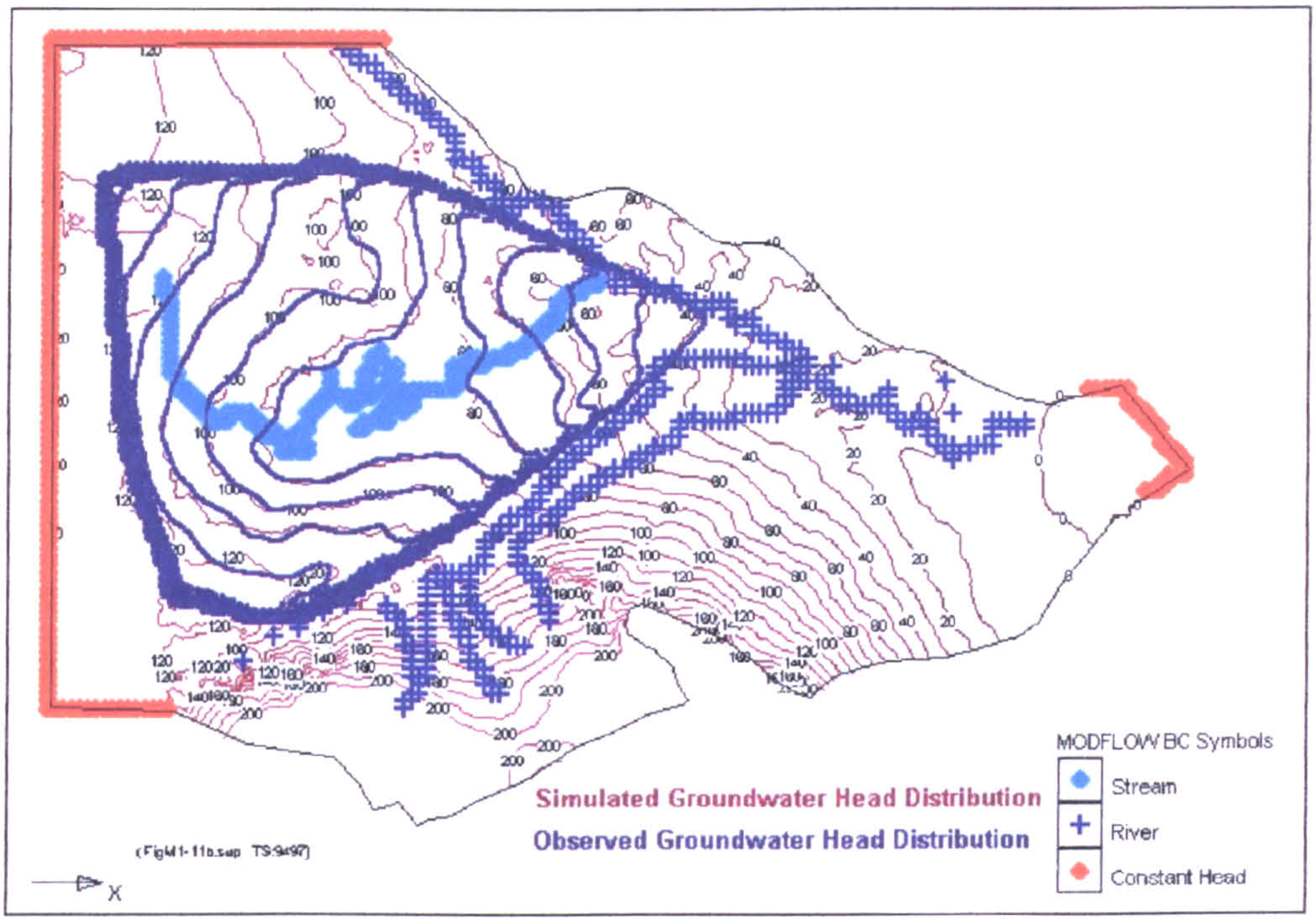


Figure 3.13: Simulated and observed groundwater head distribution (AyEE, 1990). Only observed borehole data was available for the Northwest area.

Data on transient heads were available from a number of well hydrographs for which depths to groundwater have been measured, somewhat inconsistently, on a monthly basis. Records were available for seven wells for the period 1963 to 1978 whereas for the rest, for varying periods from the early 1980s. Figure 3.14 shows three hydrographs representing various hydrogeological features of the basin. Head responses are variable in both the timing of head rise and in the persistence of high heads. Increases in head tend to commence in April-May, with rise rates greater than the equivalent rates of decline. Variability in the persistence of the relatively high heads and the difference between rates of rise and decline are attributable to local boundary head controls provided by wetlands and lakes and demonstrate an intimate relationship between groundwater and these surface features. The hydrographic data in the Northwest of the province (i.e. at Pehuajo) shows that heads rose significantly in a thick unsaturated section in the west of the basin from the late 1960s to the mid-1980s and then stabilized, although varying seasonally with small amplitude. The rise reflects a period of high rainfall and recharge following an extended period of low rainfall. The dynamic stabilization encountered on the hydrographs reflects approximate "aquifer full" conditions with a small unsaturated section with heads being stabilized by a combination of effluent groundwater going to wetlands and lakes and evapotranspiration directly from the water table. During high rainfall events the result of the 'aquifer full' condition is groundwater flooding. A similar rise in heads is shown for the Junín area: In the hills, historically, deep groundwater heads have occurred and a thick unsaturated section prevails. Centrally, within the plain, reasonably stable heads were observed for the 1960s to mid-1970s, with a limited depth to groundwater of about 1.5m to 3.5m. In the east, close to the coast, the data at Chascomús shows similar stable heads with shallow depths to groundwater of about 0m to 2m.

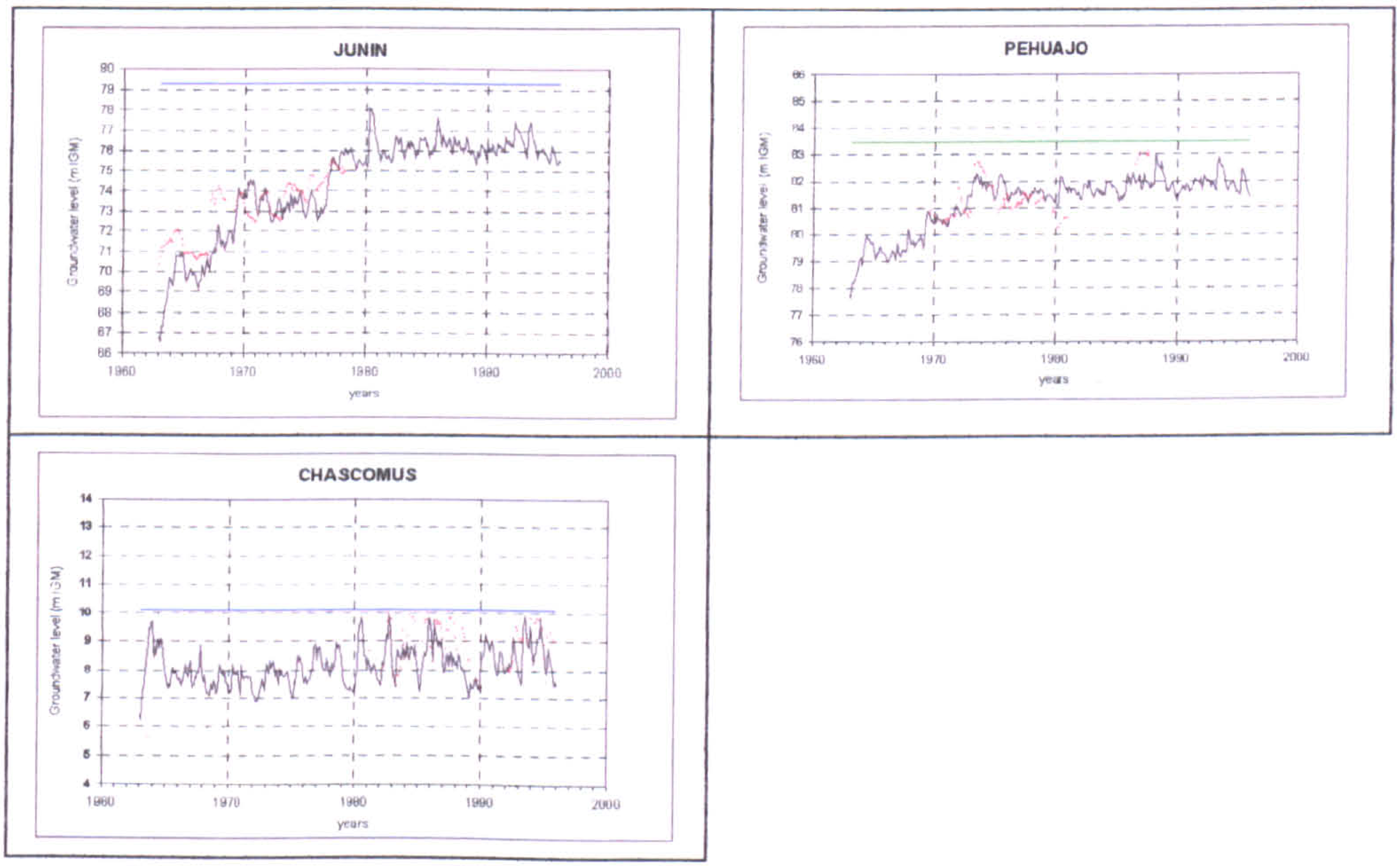


Figure 3.14: Simulated (continuous line) and observed (red dots) groundwater hydrographs at key locations.

3.2.4 Existing Land Use Practices

Both agricultural and meat production in the Salado basin are important at a national level. For example, for the period 1994/97 the production of maize, wheat, sunflower and soya in the Salado region constituted 25% of the total production recorded for the country. The production of meat production (at over 1.8 million tonnes per annum) represents every year about 30% of the total production of the country.

Mixed agriculture, combining livestock and cropping, is predominant, although livestock occupies approximately 70% of land area. In areas with suitable soils crops are grown, usually in rotation with livestock activities. Figure 3.15 shows the distribution of land use in the area, as interpreted by INTA (the National Institute of Technological Support to Farm Enterprises) from satellite imagery (Landsat TM, dated 1997). This figure, supported by Government statistics, shows that it is only in the upper reach of the Salado area that crops predominate over livestock. In the Zona Deprimida and in much of the Ao Vallimanca/Ao Las Flores valley land use is almost exclusively low intensity "cria" (breeding) livestock. In much of the Northwest cropping is also important, with summer crops in rotation with livestock (complete stock cycle and/or "wintering"). The situation in the foothills of the south is similar, though with wheat as the principal crop. Along the lower Rio Salado, livestock dominates, with some cropping, and with an important amount of dairy activity.

During the last 15 to 20 years crop husbandry has advanced considerably in the area, in response to rising prices and increasing export opportunities, and production has become more efficient. Livestock and pasture management have not advanced so rapidly or comprehensively. Some intensification has taken place but, viewing the area as a whole, livestock numbers have not risen and stocking rates continue to be well below the optimum productivity.

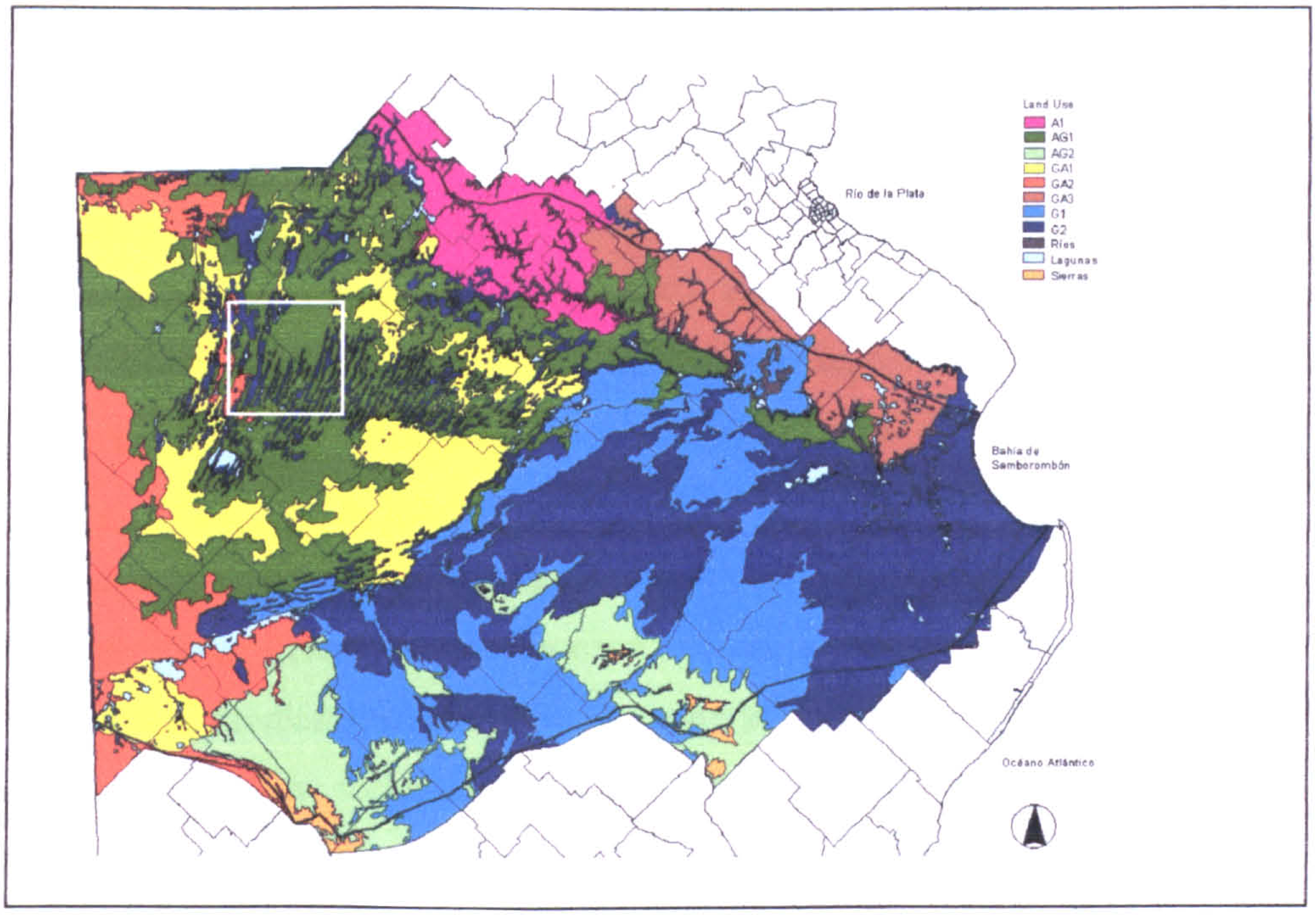


Figure 3.15: Land Use Distribution (interpreted from satellite imagery). A1 (agricultural area); AG1/2 (agricultural-livestock); GA1/2/3 (livestock-agriculture); G1/2 (livestock).

3.2.5 Water Resources

The Salado Basin does not at present have any organization that can exert a strict control in the use of the water resources of the region, in terms of abstractions and discharges. There is written Water Code but it is still awaiting its full implementation.

Within the basin the main uses are related with the supply of potable water to localities, water for livestock and, predominantly in the south of the basin, water for irrigation. Irrigation usage has grown continuously throughout the years but, unfortunately, the province does not keep any systematic record of abstractions. Most of the water is abstracted from the aquifers and very little supply comes from the watercourses.

Underground flows, driven by the very low topographic gradient, are very low and little movement of the water accumulated into storage has occurred. Therefore a high content of salts and gypsum, accumulated during the earlier deposition of sediments still persists. Also, most of the groundwater is close to saturation with calcium carbonate, which leads to a widespread situation of high salinity and alcalinity. Groundwater resources of good quality (with an content of total dissolved solids of less than 1000 mg/l) are located in the southern and northern fringes of the basin. In the central area, the vicinities of 25 de Mayo and Viamonte also have good potential for abstractions, indicating the location of areas where the recharge takes place directly to the regional aquifer system. Within the NorthWest region DYMAS (1974) reported salinity measurements of up to 2000mg/l, showing the high influence of the highly brackish water present in the Araucana Formation. The presence of water with these characteristics, located in the upstream parts of the basin, provides further evidence of the low recharge to the regional system that took place prior to the 1970s. However, this situation has been locally modified by the presence of fresh water lenses stored in the tops of the dunes created from the increase in regional rainfall that took place after the 1970s. This defines a very delicate equilibrium in the region with the existence of thin layers of very good water quality underlain by layers with high concentrations of salt.

The surface water system does not present a better situation in terms of quality as a consequence of groundwater discharges, the dissolution of Post-Pampeano sediments, catchment transfers (like the one from the south western lakes) and the reception of water from land use drainage. Existing records along the Jaureche-Mercante canal show a salt content that varies from 7800 mg/l to 17600 mg/l, whereas the range for the Salado river goes from 5400 mg/l to 10600 mg/l.

Further to the issue of salinity, the water resources of the basin started to show signs of contamination as a consequence of an increase in discharges of untreated (or badly treated) effluent, and the discharges with a growing content of residual fertilizers and herbicides.

Despite the fact that watercourses and lakes contribute in a very small proportion to satisfying the needs of water consumption, they constitute a very valuable element for recreation and tourism, as most of the tourism activities in the province are located in the surroundings of the lakes and are mainly related to camping, fishing and, to a lesser extent, hunting.

3.2.6 Environmental Assets of the Basin

The Rio Salado catchment is part of an ecological zone known as *Pastizales de la Pampa Humeda*, within the biographic region of Argentina known as *La Pampa*. This large flatplain once supported extensive, treeless, pampasic grasslands. Now, virtually nothing of this natural habitat remains, the area having been altered beyond recognition by both cultivation and cattle ranching.

Within this context there are several environmental issues relevant to the entire catchment. Examples include: the *Bahia de Samborombon* which is a Ramsar site (Ramsar, 1971) and which is probably the most important ecological feature in the catchment; the whole complex of rivers, riverine wetlands, lakes and coastal wetlands is of great importance to bird populations; the wetlands that occupy the interdunal depressions and which could play a vital role acting as green filters to dampen the effect of the increase use of fertilizers and herbicides that will take place with the increase in agricultural activity.

Any potential flood mitigation measures put forward for the basin will have to be environmentally assessed properly in order preserve features of the existing complex flood regime, which involves seasonal and long-term cycles, and constitutes a key factor in the maintenance of the dynamic ecology of the wetland/grassland systems. Also, the lower catchment of the Zona Deprimida and the lower reach of the Rio Salado are the receptors of the effects of human activity (especially agriculture) in the headwaters of the catchment, and care will have to be taken to avoid further detriment to water quality and problems of eutrophication of the lakes. Figure 3.16 shows a conceptual model of the environmental interactions in the area.

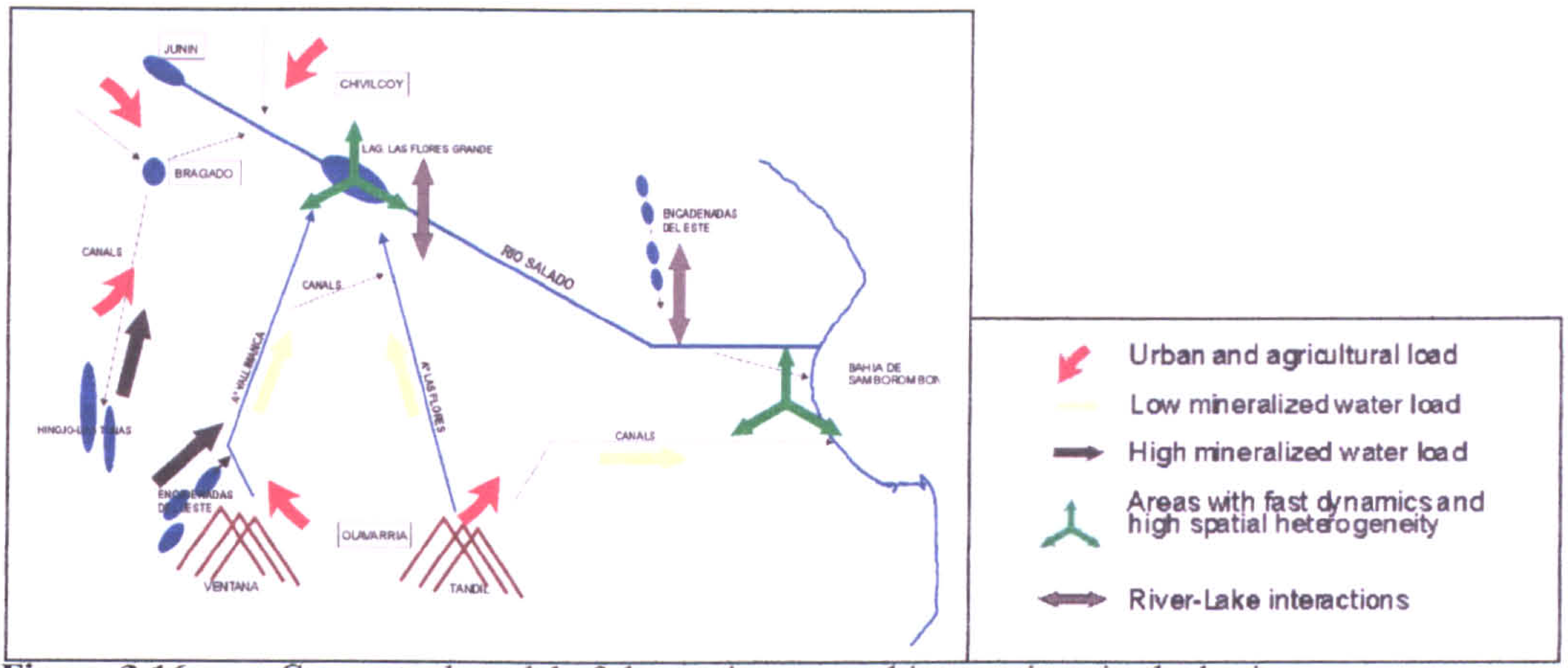


Figure 3.16: Conceptual model of the environmental interactions in the basin.

3.2.7 Drainage Network and Hydraulic Works

One of the outstanding characteristics of the Salado region is the lack of a well-developed drainage network, consistent with the current generation of runoff in the area. Figure 3.17 presents a classification of the basin according to its current drainage density. The different areas encountered can be grouped in three major surface drainage systems: A) the system that comprises the three main rivers of the basin (Salado and its two major tributaries Vallimanca and Las Flores), B) the Northwest region with its lack of a natural fluvial network and C) the Southeast region with the streams that descend from the Tandilia hills and the canals that extend these streams to discharge into the sea. The three regions, and a further proposed operational subdivision (Halcrow, 1999) are shown in Figure 3.17.

Each system has a different response to the rainfall according to the geomorphic and hydrologic characteristics of the region. The Rio Salado presents two distinct reaches: the upper reach with a fluvial valley and a well-defined network of tributaries entering from its left bank, and the lower reach with a marked absence of fluvial features. The latter is formed by a sequence of wind-deflated depressions interconnected by short, incised reaches. The lack of a well-defined floodplain in the lower reach leads to restriction of out of bank flows.

The Arroyo Las Flores is the stream of the region that most closely approaches a fluvial, regime channel, with an active floodplain either side of the river, close coupling with the streams descending from the Ventania hills and rapid response to heavy rainfall events.

The Arroyo Vallimanca/Saladillo, located north of the Arroyo Las Flores, is the slowest of the three streams in terms of its response to a storm event. En route to its confluence with the Rio Salado, the course of the Vallimanca has to cross a field of dense, parabolic dunes that poses a severe restriction to the conveyance of the flood flows. Due to the very low gradient of the river, and the absence of a smooth floodplain, the water accumulated in each of the depressions behind the dunes stays on the surface for months until it eventually finds its way downstream via flow in-bank in the channel.

The Northwest system is defined by not having a natural drainage network. However, under extreme conditions, the appearance of groundwater on the surface can develop temporary watercourses along the interdunal depressions. In the late 1980s, this region was artificially connected to the Rio Salado by a drainage canal (Jaureche, Mercante and Italia) that starts in the Hinojo-Las Tunas lake system. This canal collects most of the excess runoff in the region and discharges it into the Rio Salado.

The Southeast region has a series of small watercourses that start in the Tandilia hills. They have steep gradients and high conveyance capacity for water and sediment as they flow down the hill and fan surfaces, but they rapidly lose capacity as they leave the fan area and enter the central depression of the basin. From this point to the sea a series of flood relief canals that intercept runoff and artificially continue the stream channels to the sea.

Finally, there are a large number of structures (mainly gates and stop locks) built with the original purpose of regulating flows into drainage canals and/or maintaining certain levels in water bodies. Due to the absence of an adequate operational capacity within the current institutional framework, most of the structures have deteriorated, and many are not longer operable. Those structures that are operated, are left under a very weak control without proper and clear rules.

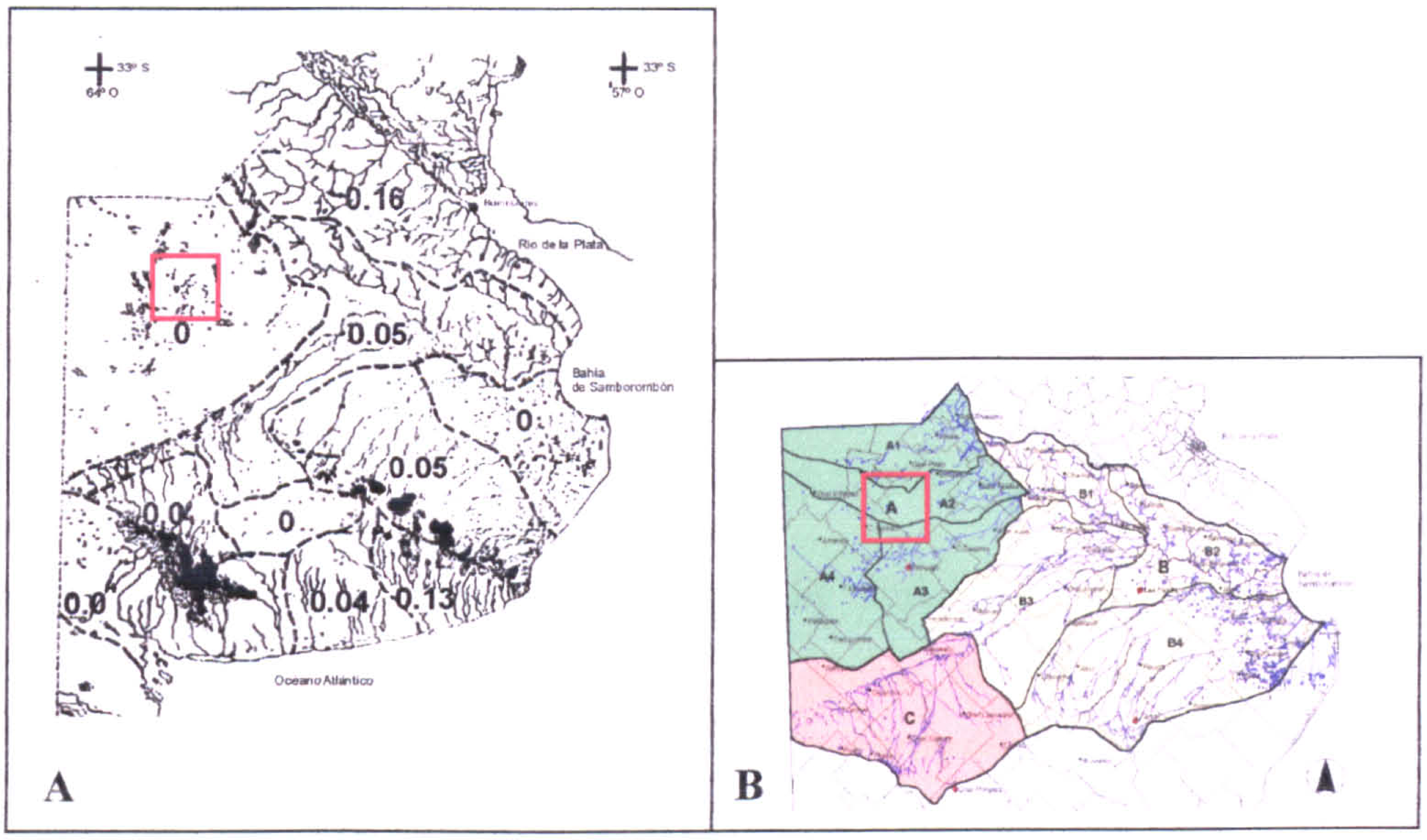


Figure 3.17: **A**: Drainage Density (expressed in km/km^2). **B**: Major Surface Sub regions.

3.2.8 Current Institutional Arrangements

There are three provincial ministries that have some responsibility for activities and resources in the basin: Works and Public Services (*Ministerio de Obras y Servicios Públicos – MOSP*), Agricultural Affaires (*Asuntos Agrarios*), and Production and Employment (*Producción y Empleo*). Under MOSP, the Provincial Hydraulics Division (*Dirección Provincial Hidráulica – DPH*) has the day to day responsibility for the execution of the planning, design, supervision of construction and maintenance of all hydraulic works within the province.

The present institutional structure has strengths and weaknesses. Amongst the strengths are the established presence of DPH through its district offices, the close relationship that they have with the local Municipalities, plus the relatively well developed private support systems for agriculture. Weaknesses that must be addressed include fragmentation of the system, which operates within a culture of independence, lack of attention to medium and long-term planning, and the tendency to be reactive to problems and to view them in a local context rather than a regional one. A major problem is the limited resources available within the government sector and, related to this, the high degree of centralisation in managing funds, which are concentrated in the headquarters, outside the basin boundaries.

3.3 Problem Diagnosis

3.3.1 Development Potential and Restrictions to the Development of the Area

The economy of the area is dominated by agriculture and there are no indications of a change, nor indeed does appear to exist much scope for significant development in other sectors. In particular, the Northwest will feature an increase of the area of cropping, but this will still occur in combination with beef production and dairy development. The Central area (south of Northwest and north of Ao Vallimanca) will move towards complete cycle beef production and, where conditions permit, cropping. The Rio Salado corridor is expected to show an increase in urban sprawl and an intensification of current enterprises. The Southeast and Southwest are unlikely to change, apart from some intensification of cropping and expansion of dairying (Halcrow, 1999).

Any planning strategy must, therefore, concentrate on addressing the factors that are currently limiting production in the catchment, but only where there is the potential for increase, and where this can be achieved in a sustainable manner. This implies a combination of improved physical conditions plus non-structural programmes to allow producers to take advantage of lower risk levels. From the foregoing, the indications are that most growth potential lies in the Northwest, the Zona Deprimida and the Ao Vallimanca/Ao Las Flores valleys whereas, in other areas, the trend is likely to be towards intensification of current production systems.

The outstanding physical constraint is the occurrence of widespread and long duration flooding and waterlogging events that result from the inadequacy of the natural drainage system to convey and/or store the rainfall excesses without inundating large areas for long periods, with adverse impacts on the environment as a whole. In this context, flooding is defined as the presence of water above the ground surface, whereas the term waterlogging is used to describe the existence of saturated soil or ground water near the surface, taking 0.50m below ground as a usual threshold.

These two phenomena represent hazards to general farming activities and a distinction is made between the terms as a function of the likely impact and consequences they pose. Flooding is mainly related to losses expected in the livestock sector as the water standing on the surface mainly affects the medium to long term availability and quality of pastures. It is also well correlated with physical damage to the infrastructure of the farm. Waterlogged areas are assumed to produce damage related to cropping activities as the presence of water within 0.5m of the ground prevents farmers from tilling and harvesting as access from vehicles is severely constrained. It could be argued that there will be agricultural damage too in those areas subject to surface flooding, but this is usually very small compared to the losses sustained in waterlogged areas.

In addition to the physical constraints there are also important institutional, agricultural, social, economic and financial constraints that, together, impose a limitation to the sustainable growth of the region. Table 3.4 summarises the main constraints identified in each case.

Institutional Constraints: An existing Centralised Institutional System Lack of Co-ordination beetween Agencies and with the Private Sector Lack of Human, Physical and Financial Resources for Management Unsustainable Mechanisms for Operation and Maintenance Lack of Effective Monitoring and Evaluation Procedures Legislation and Lack of Enforcement	**Agricultural Constraints:** Unwillingness of producers to invest Poor Rural Road Access and Drainage Flooding and Water Logging in Livestock Areas Degradation of Soils Beef Herd Intensification Lack of Producer Skills in Farm Business Management
Physical Constraints: Variable Climatic Conditions Poorly Developed Drainage Systems Soils and Quality Groundwater and Quality Uncontrolled River and Drainage Systems	**Social Constraints:** Lack of Awareness and Co-operation Amongst Producers Urbanisation of Producers Inherent culture of independence
Economic and Financial Constraints: Economic cost of Land Improvement Bias in the Ownership of Productive Resources High Level of Farm Taxation High Cost of Agricultural Credit	

Table 3.4: Summary of the Main Constraints to the Development of the Region.

3.3.2 Conceptual Understanding of Flooding Mechanisms in the Basin (Groundwater and Surface Water Issues)

Having identified the importance that flooding (and waterlogging) has in terms of its physical impact in the region, and bearing in mind the heterogeneity and complexity of the physical features of this area, deepening the understanding of the response of the basin to rainfall posed a challenge to be addressed as part of this research.

Flooding (or waterlogging) was explicitly described in terms of "rainfall excess" and not runoff in order to encompass a wider range or driving mechanisms, including:

(i) ponding of water in the numerous depressions that occupy the low lying central areas of the basin (Depression Zone), retained on the surface due to the low infiltration capacity of the soils and the flatness of the terrain that impede its runoff.

(ii) extensive floodplain flooding due to overbank flows from the major rivers of the system: Salado, Las Flores and Vallimanca (fluvial flooding), or overland flow along the slopes of the southern hills.

(iii) ponding of water in the interdunal depressions that dominate the landscape of the Northwest area caused by exfiltration from groundwater. This differs from (i) in that in this case water exfiltrates from the ground whereas whereas in (i) water is unable to enter the ground. This is similar to the description provided by Morita and Yen (2002) as saturation from above and below ground.

The types of flooding described here can be further classified and analysed according to the likely magnitude of its impact and the degree of connectivity of the flooded areas. The following Table 3.5 presents the results of this analysis.

Ponding of water	
Cause	Direct rainfall impacting on the ground; low infiltration capacity of the soil; very flat terrain leading to negligible horizontal flow (surface or subsurface).
Duration of event	Weeks to months. But it varies depending whether this event is superimposed to fluvial and/or overland flooding.
Velocity	Negligible due to the flatness of the relief.
Depth	Low (approx. 0.5m)
Flood extent	Isolated patches of water not initially connected but become connected once a topographical threshold is exceeded. The connection can also take place following an external stress such as fluvial flooding.
Area of predominance	Central part of the basin (Depression Zone) and coastal fringe.
Fluvial Flooding	
Cause	In-bank capacity of streams less than that required to convey

	flows generated for events of a given magnitude (generally less than 2- years return period)
Duration of event	Weeks to months. In the Las Flores system the duration does not normally exceed one or two weeks. Overland flow situations in the southern hills last a few days to a week.
Velocity	Flood flow velocities vary from low velocities in the lower reaches of Vallimanca and Salado, to medium values in the Las Flores and finally to fairly high values in the streams descending from Tandilia.
Depth	Medium to high flood depths of the order of 2m to 3m along the floodplain of the Salado.
Flood extent	Predominantly concentrated along the corridors of the three main rivers Salado, Vallimanca and Las Flores with an active floodplain width that can reach 20km.
Area of predominance	Basin wide except in the northwest region.
Groundwater-Induced Surface Flooding	
Cause	Infiltration in excess of evapotranspiration, soil moisture capacity and horizontal fluxes, coupled with very small regional gradients and with the existence of landform controls on the surface.
Duration of event	Months.
Velocity	Negligible during the early stage of the event but rises when the flooding spreads along the interdunal depressions.
Depth	Depths are mainly controlled by the crest elevations of the parabolic dunes along the interdunal depressions that can reach a relative altitude of the order of 3m.
Flood extent	Initially, the flood extent features a set of isolated ponds behind parabolic dunes that then become a series of stream bodies along the elongated, interdunal depressions. Ultimately, the latter coalesce into a single flood flowing towards the lowest regional part of the area.
Area of predominance	Northwest region of the basin.

Table 3.5: Descriptors for each flooding mechanism.

To complement the analysis presented in the table above, the following Figure 3.18 presents a conceptual representation of the response of the basin to each flooding mechanism.

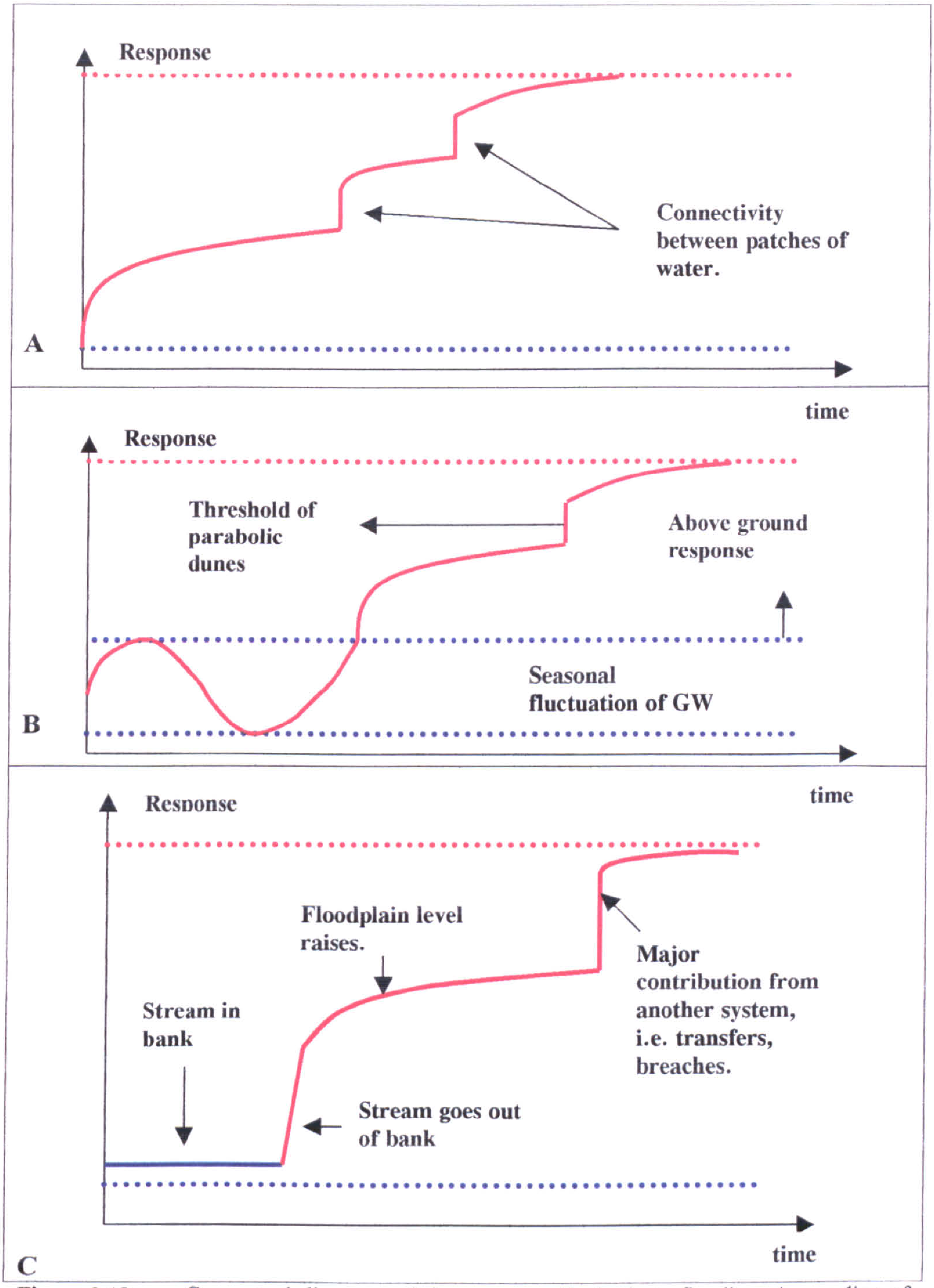


Figure 3.18: Conceptual diagrams of the response of a basin to flooding. **A:** ponding of water, **B:** groundwater-induced flooding and **C:** fluvial flooding (dotted red and blue lines: maximum and minimum responses respectively).

Fluvial flooding occurs as a consequence of a drainage system that is still adjusting to the current runoff regime. The drainage system is superimposed on top of a relief formed by wind blown features that constrain the conveyance of out of bank and overland flood flows. This situation is manifested particularly along the entire course of the Arroyo Vallimanca and in the lower reach of the Rio Salado. In the first case, the topographic restrictions cover the whole inundated width (which is not yet a floodplain) to limit the conveyance of flood flows and slow down the return to an inbank situation, leaving areas with standing water for months. In the lower Rio Salado the topographic restriction acts earlier in the flooding process, limiting the egress of water from the channel, causing important backwater effects and delaying the downstream conveyance of flood water. Figure 3.19 shows a plan view of the lower reach of the Rio Salado and a typical cross section featuring a fluvial constriction.

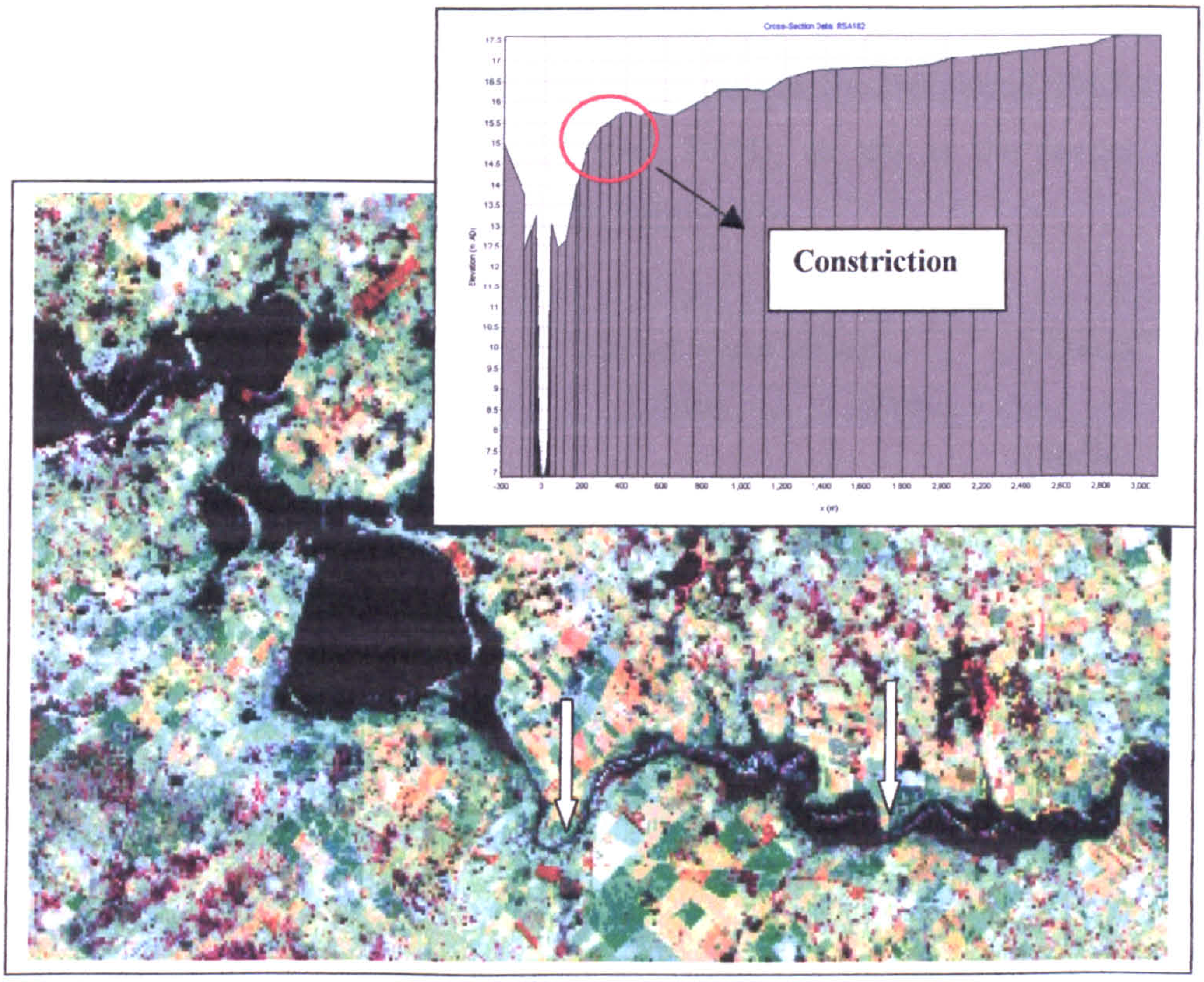


Figure 3.19: Plan view and cross section on the lower reach of the Rio Salado showing fluvial constriction. The white arrows point at fluvial constrictions. Note expansion of flooding upstream of constrictions.

A dominant discharge analysis was performed and the results are presented in Table 3.6. It is worth noting that the in-bank capacity of the Rio Salado, at Achupallas, is much lower than the calculated dominant discharge, which suggests a severe under capacity to convey the runoff from the catchment, including the portion of the Northwest area linked via the Canal Jauretche-Mercante.

River / Section	Dominant Discharge (m^3/s)	2-year return period flow (m^3/s)	Bankfull discharge (m^3/s)
Salado – Achupallas	132	42	22
Salado – Guerrero	325	284	300
Vallimanca – Road 226	41	85	45
Las Flores – Alvear	73	79	90

Table 3.6: Dominant and bankfull discharges at key selected areas.

Finally, Table 3.7 presents a summary of the statistical analyses of observed flow records in the main watercourses, carried out for the period 1967-1995 (source Provincial Hydraulic Authorities, DPH), as this is the period that contains the largest amount of available information.

Location	Mean Flow (m^3/s)	Flow for selected return periods			Q max [1] (m^3/s)
		2yrs	10yrs	100yrs	
Salado *(Achupallas)*	73	42	161	478	446 *(1985)*
Salado *(Guerrero)*	430	284	912	2358	1798 *(1980)*
Vallimanca *(Road 226)*	140	85	306	868	610 *(1969)*
Las Flores *(Alvear)*	100	79	189	387	349 *(1980)*
Los Huesos *(Miranda)*	26	17	55	143	138 *(1980)*

Table 3.7 Flood Flows for different return periods based on the statistical analysis of observed flow.

Groundwater-induced surface flooding is a direct response of the regional hydrogeological system and micro-forms in the surface relief. For regional hydrogeological purposes, the system can be considered as unconfined, with its base defined at the top of the Parana Formation. Apart from the fringing mountain and hill areas at the boundaries of the basin groundwater gradients are very gentle with a regional flow to the east to the coast. The ubiquitous presence of wetlands and lakes (progressively increasing in frequency from west to east), is dictated by the very gentle topographical gradient and very thin unsaturated zone, indicates that the groundwater regime is closely coupled with, and constrained by, the surface water regime. Geomorphologically, a feature of the plain is the lack of eroded river courses away from the principal rivers and arroyos. This shows that a conventional surface water drainage system with significant direct runoff from rainfall is not dominant in the Northwest region.

Because of the small unsaturated thickness, the water table is directly subject to evapotranspiration, which is a significant control on heads. When major recharge events occur normal evaporative losses are overtaken, heads rise rapidly and groundwater rejection takes place, giving rise to flooding and the subsequent creation of non-perennial lakes and the areal extension of perennial lakes. Depending upon their topographical configuration and the amount of groundwater rejection, the lakes can join and major groundwater flooding can ensue. The process is such that surface flooding induced by the groundwater catchment is a transient situation. During non-flooding periods the groundwater system is very localized, with recharge being balanced to a large extent by evapotranspiration, resulting in limited lateral groundwater flow contributions to regional flows. This indicates that the regional flow is relatively small, which is consistent with the relatively small hydraulic conductivity, the very gentle regional gradient and the relative high groundwater salinity. Figure 3.20 shows a conceptual representation of the groundwater-induced surface flooding process.

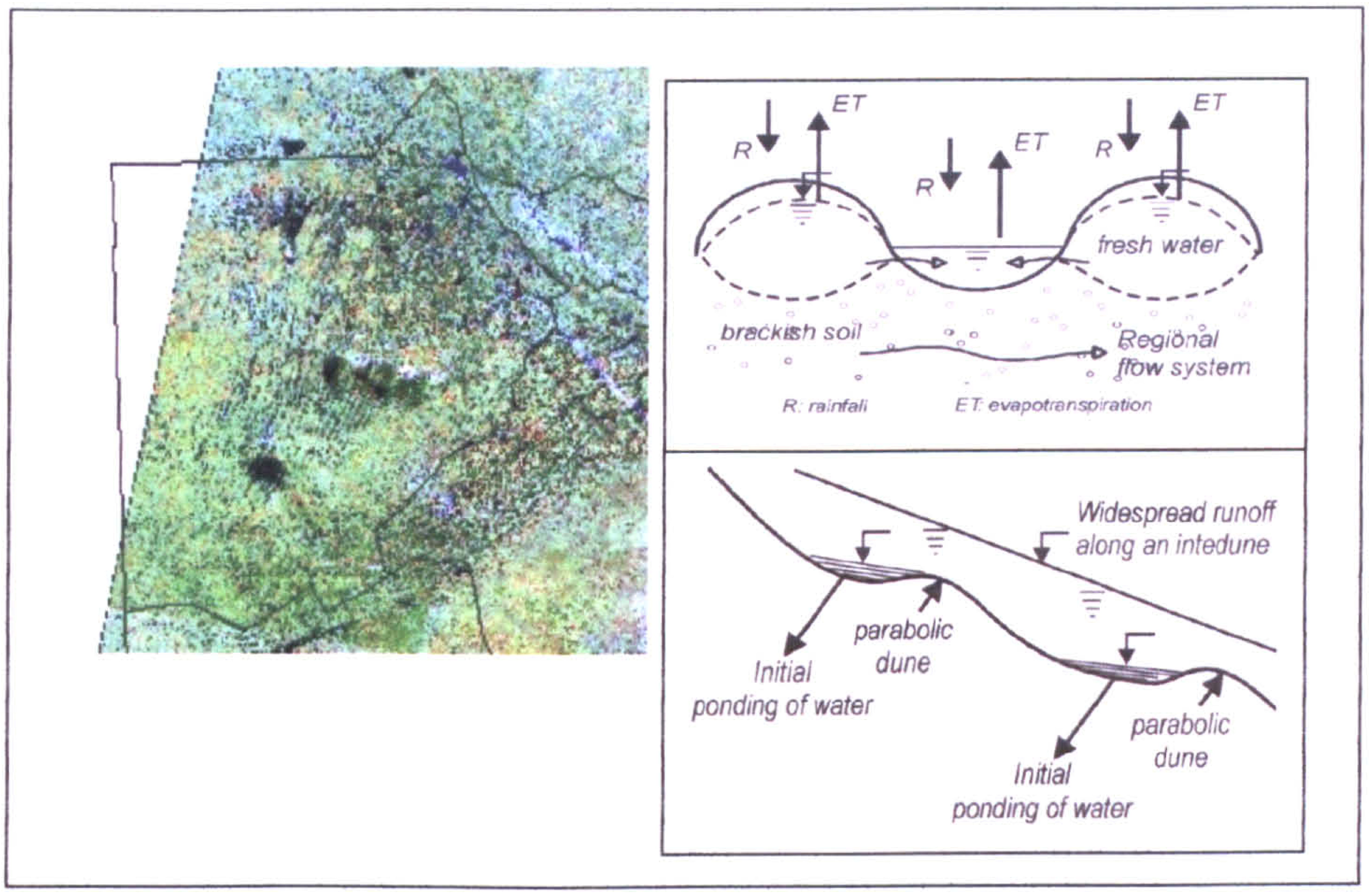


Figure 3.20: Conceptual understanding of groundwater induced surface flooding in the dune field of the Northwest region.

Based upon the conceptual understanding of the system, the flow balance for the basin can be formulated as follows:

Precipitation = runoff + infiltration + interception storage + evaporation from open surfaces with the intercepted water

Infiltration = actual evapotranspiration from the unsaturated zone + lateral subsurface flow (interflow) + recharge

Change in groundwater storage = recharge ± groundwater flow - actual evapotranspiration from the saturated zone ± groundwater discharge to rivers, wetlands and lakes

In order to give a fuller appreciation of the magnitude and extent of the problem the following mosaic (Figure 3.21) presents a complete satellite image for the widespread flood event that took place in 1993 along side photographs of flooding in the central depression area.

Having established the main flooding mechanisms in the region, this research concentrates on GW-SW interaction for a number of reasons, including:

(i) its widespread extent, and its uniqueness in terms of the magnitude of flooding and the interaction with relief features,

(ii) the need to implement major capital investment in flood management schemes to mitigate the problems associated with groundwater-induced surface flooding,

(iii) the strong correlation that exists between a reduction in the risk level, land use change and/or increases in land use productivity, and

(iv) the potential effect that flood management measures could have on the delicate balance between water resources and environmental equilibrium.

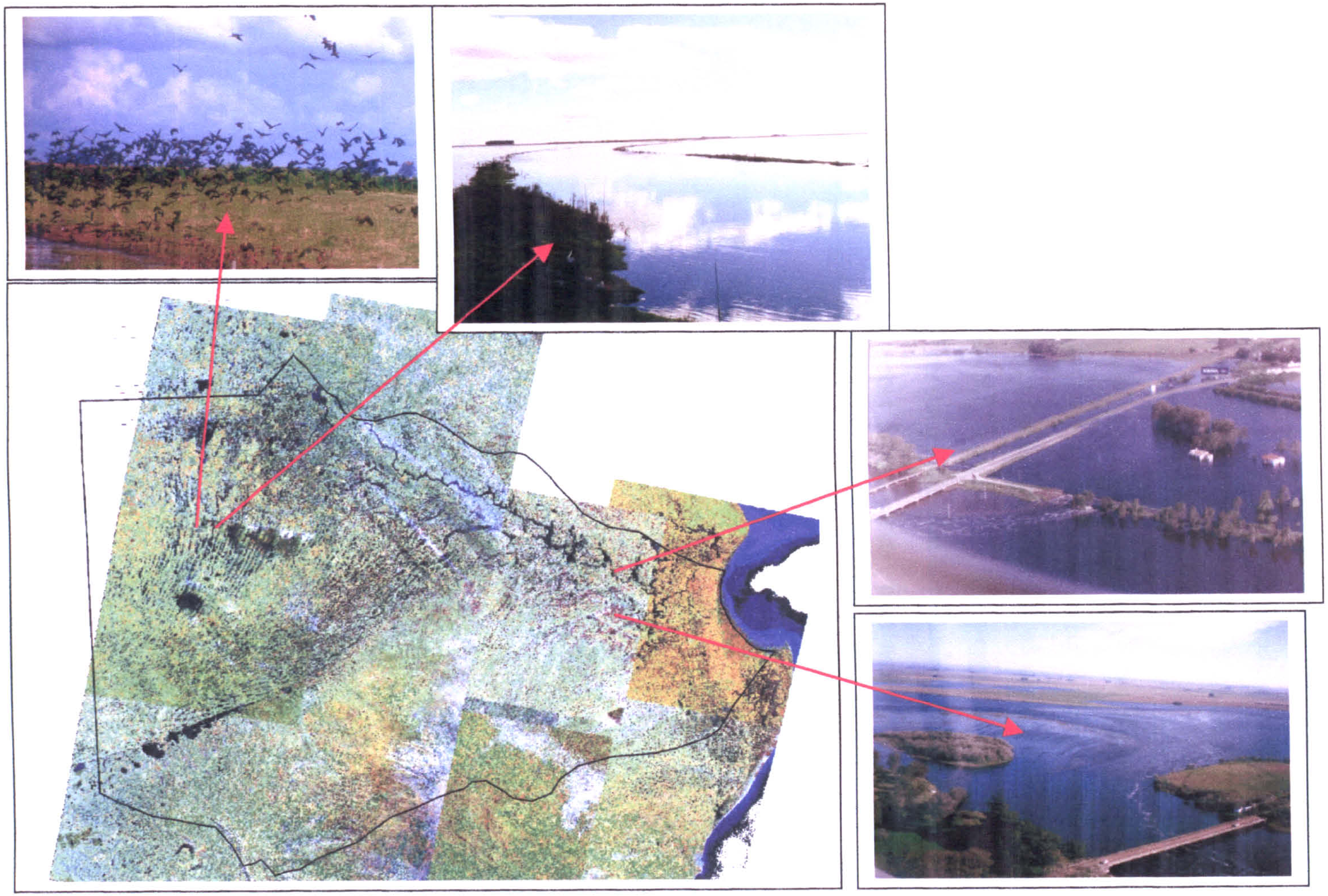


Figure 3.21: Conceptual understanding of groundwater induced surface flooding in the dune field of the Northwest region.

Photographs left to right: bird life in the Northwest; flooding in the canals and two views of flooding in the depression area.

3.4 The Integrated Master Plan

Diagnosis of the problems in the Salado basin identified that there are several restrictions on the development of the full economic potential of the region, including widespread and long duration flooding and waterlogging events which have the most detrimental impacts on the land and in the population.

In response to this situation a World Bank funded study was carried out, to prepare an Integrated Master Plan (IMP) for the sustainable development of the catchment. The problem has been the subject of attention by Government since the beginning of the 20th century, but this study was the first attempt at an integrated approach to the problem at a regional level. The studies started in 1997 and the final report of the master plan was presented to the provincial authorities in 1999 (Halcrow, 1999).

With respect to the Master Plan, the overall policy or goal of the Government was to realise the economic potential of all water related activities in the Rio Salado Basin. To achieve this goal the Master Plan had three principal objectives:

(i) to bring about a reduction of the negative impacts which floods and droughts have on the economy of the catchment and, therefore, the province and the country;

(ii) To improve the economic conditions of the catchment through sustainable development of its potential and, in particular, economic activities related to agriculture and livestock enterprises; and

(iii) To protect and enhance the environmental value of the catchment and, in particular, its wetlands.

The Master Plan provided a framework for balanced social and environmental development of the basin, consisting of a wide range of measures designed to address the constraints identified during the diagnosis. They can be structured under the following headings:

(i) an institutional framework to enable effective planning and management,

(ii) non-structural measures to improve water management, agricultural production and environmental protection, to increase public awareness and to promote tourism,

(iii) supporting measures to promote economic development in the agricultural sector, and

(iv) structural measures to provide improved drainage and flood mitigation.

Table 3.8 presents all the costs associated with the measures of the IMP and Figure 3.22 presents a map with the proposed structural measures. Cost estimates for the structural measures have been calculated based on prefeasibility level designs for the works and include land acquisition, study, design and supervision, environmental mitigation measures, and physical contingencies. The economic analysis generally supported the adoption of a design standard of 1:10 years for the drainage works in the Northwest and the flood relief measures along the Rio Salado, Ao Vallimanca and Ao Las Flores corridors, as consistently higher economic returns were obtained in all sub-regions of the Northwest compared to a 1:5 years standard. For the Zona Deprimida, where economic returns were much lower, a standard of 1:2 years has been used for the design of flood alleviation measures.

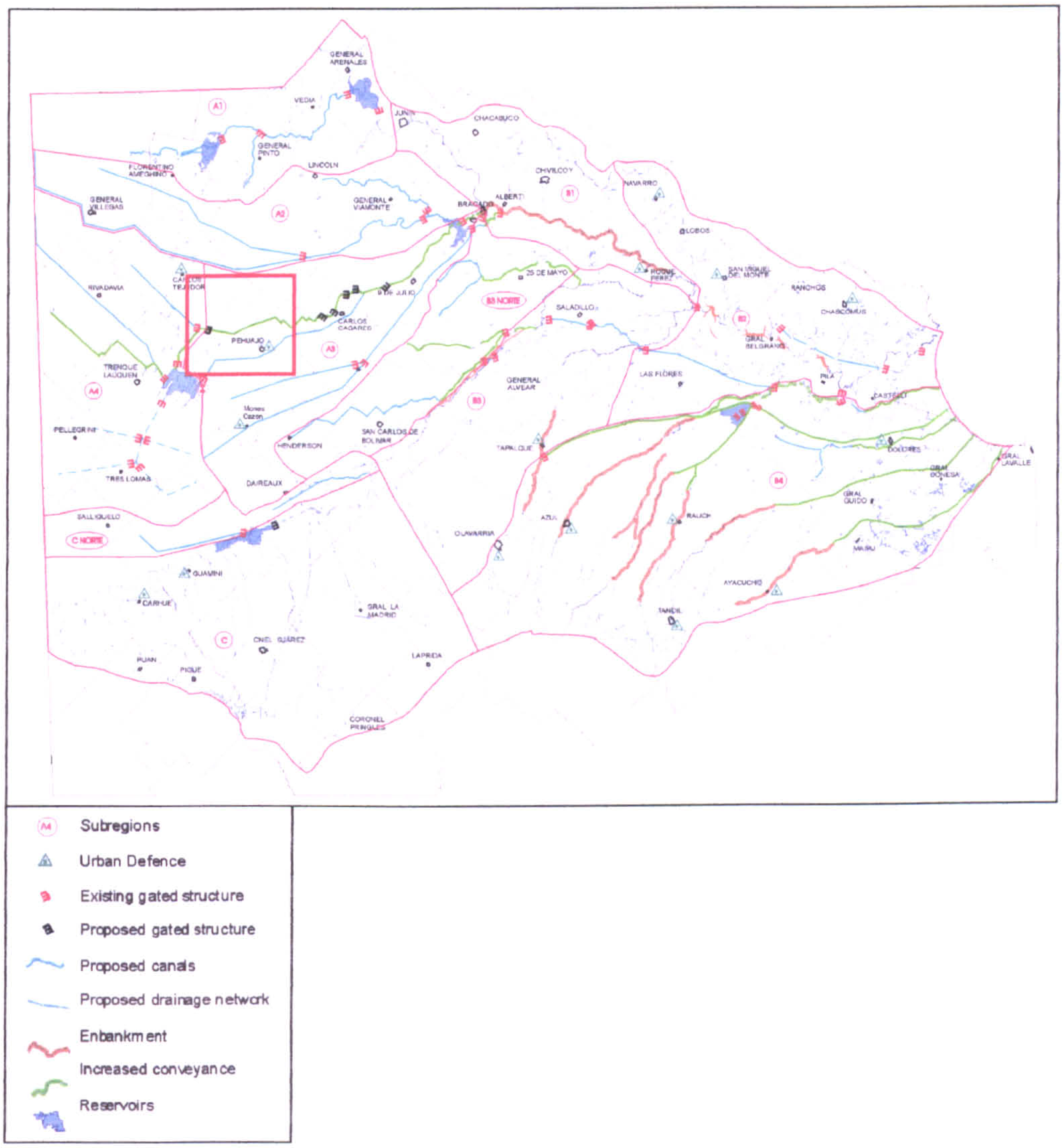


Figure 3.22: Río Salado Master Plan. Proposed Structural Measures.

Package	Description	Costs (million US$)
Structural	Improved drainage in the NorthWest region.	406
	Flood mitigation in fluvial corridors (Salado, Vallimanca and Las Flores)	863
	Rehabilitation works in the Depression Area.	561
	Urban Flood Protection Works	55
Non Structural and institutional	-	59
Total		**1944**

Table 3.8 Summary of Costs for the Implementation of the IMP. Costs were estimated in 1999 where the exchange parity between the US$ dollar and the $AR was 1.

Appendix A provides more information on the IMP and its social, economic and environmental impacts.

With implementation of the measures proposed in the Master Plan it is expected that widespread and significant increases in production in the agriculture sector will result. The projected annual increases in production, in terms of crops, livestock and dairy are also included in Table 3.9. Values are given both as tonnes and as the percentage increase on present production at full project development. Overall, these equate to an increase of about 10% on present annual production, representing over 1 million tonnes of crops and 150,000 tonnes in the livestock sector. Benefits to crops and livestock have been measured as net incremental benefits, that is the difference between the net value of farm production in the *without project* and the *with project* cases. Benefits include: reduced losses of crops and livestock production and on-farm infrastructure caused by flooding/waterlogging, and changes in land use as a response to reduced risk of flooding/waterlogging. The benefits attributable to public infrastructure in rural areas have been estimated as the total value of avoided flood damage to the infrastructure, that is the reduced cost of repair of damage. Finally, all project benefits have been weighted by flood event probabilities in order to derive *average annual expectation of loss.*

	A	B	C	Total
Productive land (km^2)	5131	6652	588	**12371**
Productive land benefited (km^2)	4726	1692	438	**6856**
Increase in agricultural production (%)[1]	4 to 22	0 to 11	8	**10**
Increase in meat production (%)[1]	13 to 18	2 to 6	2	**8**
Increase in dairy production (%)[1]	12 to 31	1 to 13	4	**11**

Table 3.9: Estimated Benefits derived from the implementation of the IMP.
[1] the range of increase is indicated as it varies with sub-regions within a region.

The success of the IMP and its sustainability will depend on its social impact, that is the number of people who will benefit and those who will suffer detrimental impacts, and their distribution both within a sub-region and within the catchment as a whole. Unless there is reasonable distribution throughout, there will not be equity of benefit, the Plan will not gain widespread support and it will not encourage majority stakeholder participation.

Large-scale interventions such as those put forward in this IMP will also cause some potential detrimental effects in parts of the basin. Structural measures were planned with the prime concept that no region should experience an increase in affectation over the baseline situation; the IMP generally consists of land drainage measures in the Northwest area and flood mitigation measures along the corridor of the rivers that will receive the excess flow from the new drained areas. Land and existing infrastructure along the fluvial corridors of the Rio Salado, Ao.Vallimanca and Ao. Saladillo will be affected by the planned mitigation measures planned, such as the flood embankments. Also, in those areas where an existing permanent water body will be used for regulation purposes, a detrimental effect can be predicted for the people and infrastructure that will have to be reallocated. Despite the conceptual equilibrium between drainage in the upstream portion of the catchment and the flood mitigation measures in the downstream regions, the entire basin will be exposed to a higher level of complexity as a consequence of the operation requirements of the proposed works. This implies that the entire basin would be subject to a high potential risk if the works were not managed and maintained properly by the provincial authorities.

Finally, a strategic Master Plan of this scale has the potential for significant environmental effects. The role of the environmental impact assessment in the development of such a plan is to minimise adverse environmental effects, maximise benefits and ensure the selection of an environmentally sustainable strategy. The most important potential impacts are: the anticipated benefits to agricultural and livestock production, which provide significant regional and national economic benefit, within a general framework of sustainable agricultural development; and the potential for significant loss and modification of wetland and floodplain areas.

These two aspects are generally antagonistic in nature. It is not possible to create agricultural/livestock benefits, of the nature required by the objectives of the Master Plan, without some drainage of semi-natural areas and changes in land use. However the drainage proposals attempt to strike a balance between land use change and conservation of critical/valuable natural habitats. Mitigation of impacts will necessarily come from an iterative development process and it will recommended use of ecologically sensitive design proposals for new channels and flood attenuation areas will bring considerable ecological and recreational benefit.

3.5 Test Area

The test area is located within the North West Region of the Río Salado Basin, covering an area of 4900km^2 (70km by 70km). It is located approximately in the centre of the regional depression that collects excess water from the dune system, on either side of the Jaureche-Mercante canal. Geomorphologically, the test area lies within the region dominated by a field of longitudinal dunes that has superimposed on it a field of parabolic dunes. The location of the test area is shown in all regional figures presented throughout the above sections in this chapter.

The selection of the test area was based on the following criteria:

- <u>Groundwater-Surface Water features</u>:

  The area selected contains a significant number of longitudinal dunes where the interaction between groundwater and surface water emerges as the dominant mechanism for flooding. Groundwater emerging to the surface is collected in the interdunes and transferred downstream to the Jaureche-Mercante canal alignment.

The test area lies at the core of the zone that is most severely affected area by frequent groundwater-induced surface water flooding events: The area is well known because of the flooding incident that took place during 1987/1988.

- Availability of data:

Despite the fact that Pehuajó is the only observation borehole that falls within the test area, this time series contains observed levels between 1970 and 1980 and some scattered observations during the 1987/1988 event. The test area is covered by two groundwater head distributions: one for 1977 and one for 1988: The latter only covers the North West area. Although both distributions are more suitable for comparisons at the regional level, they were also used to analyse the performance of the local model carried out in the test area. In addition from the Agua y Energía report (1988) a set of maps showing affected areas for the following periods is available: April 1984, February 1986, March and November 1987, March and October 1988, and March 1989. This is relevant to assessing the functioning of the model in terms of reproducing the appearance and transfer of water on the surface.

- Land Use and Economics:

The test area is located within a key zone in terms of its contribution to agricultural and livestock production in the basin and, hence, of the country.

This area lies within a zone where there is a marked importance to agricultural activity, with summer crops in rotation with livestock enterprises: Also, the diary production is the most important in the whole of the North West region.

It is important to highlight that the whole area has undergone a drastic change in its land use and climate, due to the increase of annual rainfall in the region and the associated increment in groundwater levels: Prior to the 1970s, the area was arid, with no significant evidence of agricultural activity. The appearance of fresh water at the surface in the 1990s led to many new farm enterprises with a consequent increase in economic return.

Furthermore, taking into consideration the soil's suitability for agriculture, the selected area has one of the largest potentials for increasing agricultural production and, therefore, it is important to identify predict the current natural physical restrictions (including flooding) in order to be able to plan the most effective mitigation measures.

- Presence of urban infrastructure:

Finally, within this area, there are a number of settlements (the most important in terms of its population being Pehuajó) under risk due to their proximity to water bodies that frequently grow in size during flood events. Therefore, they constitute another important element within the study area in order to assess the accuracy of the model in predicting flooding levels and risks for urban infrastructure.

- Water Supply:

During the 1990s the new groundwater and surface water system reached an equilibrium in the North West area, with phreatic levels close to the surface in correspondence with dune formations and above the surface, in the interdunal depressions, in a seasonal basis.

The presence of fresh water in the dune formations, overlaying thick hydrogeological formations of brackish water, contributes to the daily supply of water to live-stock and, to a lesser extent, to human consumption. Also, the area is characterised by the presence of deep and spatially localised fresh water lenses.

Therefore, although this area would require a significant reduction in its flood risk level (hence, an increase in drainage of soils) to realise the full potential for agricultural activity, it is important that care is taken to avoid a situation where excessive drainage alters the groundwater and surface equilibrium, putting under hazard the fresh water supply capacity of the region.

- Environmental Assets:

The interdunal depressions that dominate the region are a key element of the environment as they fulfil a vital role for the survival of bird life in the area. These depressions are seasonally flooded wetlands, some of which were declared of international value and are protected by Wetlands International.

In terms of water quality, potential interventions in the area will have to be carefully treated and monitored to avoid generating further pollution with fertilizers due to an increase in agricultural activity as a consequence of the reduction in flood risk. An increase in pollutant loadings in the region could also produce further deterioration in the quality of the downstream water bodies, producing an even faster rate of eutrophication in them, as has occurred in the Bragado Lake.

3.6 Summary

The description of the physical characteristics of the Río Salado basin and the diagnosis of the flooding problems supported investigation of two of the three overarching topics of the thesis, as highlighted in Chapter 1:

- **The scale of the area**. The 170,000km^2 of the Río Salado Basin is comprised of large sub-regions, each of which is characterised by having unique geomorphic and environmental features that are intimately related to the water management issues of the entire region.

Three distinct areas can be identified: The Northwest region dominated by groundwater-induced flooding problems; the fluvial corridors along the main water courses that run across the central flatland of the Río Salado basin; and the hill slopes in the south of the basin that generate large and rapid overland flows.

- **The scale of the flooding problems**. Not only is the scale of the area large, but so also is the scale of the processes. Section 3.3 identified that GW-SW interaction is the key driving mechanism responsible for the wide spread flooding that stresses agricultural and livestock enterprises in the Northwest region.

The key methodological steps that guided the research reported in this thesis are summarised below:

(i) Analysis of the flood risk maps developed in the IMP study using the regional hydrological, groundwater and surface water models.
(ii) Development of a coupled GW-SW model (iSISMOD) making use of the existing iSIS Flow and MODFLOW models.
(iii) Application of the coupled model to a test area in the Northwest region of the Río Salado basin.
(iv) Analysis of the ability of coupled and uncoupled models to reproduce the dynamics of groundwater induced surface flooding.
(v) Based on the above, analysis of the suitability of the flood risk maps used in the IMP study to support the process of options appraisal.
(vi) Development of an outline framework for modelling studies that builds on the experience gained during the IMP study and applies the knowledge acquired from this research project.

The arguments in this chapter have been informed by the data used and the results obtained during the development of the IMP study. Therefore, it is important to present a summary of the different elements and data sources used as a starting point for the analysis presented in the following chapters (see Table 3.10).

Data and process element	Key aspects	Source
	Data	
Rainfall	Rainfall data was available on a daily basis from 1911 until 1996. Approximately 100 stations scattered around the study area were used after checking for consistency and infilling. However only 10 stations had data records from 1987 onwards.	Obtained from DPH and processed during the IMP study.
Climate	Temperature, solar radiation and humidity records were available for 14 stations from 1959 until 1996.	Obtained from DPH and processed during the IMP study.
Population	Population data was available for each of the approximately 60 administrative units located within the study area.	Obtained from INDEC (National Census Centre).
Historic records on floods and droughts	Quantification of flood and drought episodes in the province.	Books on history of Buenos Aires containing archives from the parliament and government.
Topography	Contour levels contained in approximately 400 maps at 1:50,000. Contour interval varies between 2.5m and 1.25m. Also spot heights were available in each of the maps. Regional contour information was available and was used to check the DTM processed as part of the IMP study.	Obtained from IGM (the equivalent of the Ordnance Survey in the UK) and processed during the IMP study.
Channel surveys	An accurate survey of channel cross sections was carried out with sections surveyed at an average interval of 5km.	This survey was carried out as part of the IMP study.
Surface geology	Collected from some already interpreted data from only few exploratory boreholes.	Existing literature and reports compiled during the IMP study.

Table 3.10: Summary of data and key processes relevant to the research that supports this thesis.

Geomorphology	A set of 1:250,000 scale geomorphic maps were developed from satellite imagery interpretation. A new map of geomorphic sub-regions was created using the detailed geomorphic map at 1:250,000.	The geomorphic maps were developed during the IMP study. Also background information was gathered from existing literature. This supported the interpretation of the origin of the current landforms of the area.
Hydrogeology	Regional contour maps were used for general interpretation. One map was available for the entire region with a contour interval of 10m. For the Northwest region, a set of groundwater heads was available for a dense network of boreholes for 1988; this allowed derivation of another groundwater head distribution with a variable contour interval. Conductivity and specific yield values were obtained from previous reports.	No survey was carried out during the IMP study. Data was obtained from previous reports and literature on the subject.
Land use	The land use map was obtained from an interpretation of satellite imagery supported by information contained in soil maps and statistical information on agricultural production available from census data (for each administrative unit).	The map was developed by INTA (National Institute of Agricultural Technology).
River Flows	Specific flow gauges and data from chart recorders were available for approximately 12 stations in the main watercourses.	Obtained from DPH and processed during the IMP study.
Agricultural and livestock statistics	Agricultural and livestock production figures were available for each administrative boundary.	National Economic Census.

Table 3.10 cont.

Key Processes		
Digital Terrain Model	DTMs were developed for the entire basin and the test area.	Developed during the IMP study.
Hydrological modelling	HYSIM was used to carry out the hydrological modelling.	This was done during the IMP study. Time series results were used to feed the GW-SW modelling carried out for this thesis.
Groundwater modelling	The regional groundwater model (5km grid) was constructed using MODFLOW. Surface features were accounted for only in a simplified manner.	The regional model was used in this research to provide boundary conditions for the GW-SW modelling exercises.
Surface water modelling	The regional surface water model was constructed using iSIS Flow. No account was made of GW-SW interaction.	The research in this thesis did not make further use of the regional surface water model.
Flood risk maps	Basic flood risk maps were developed to map the frequency of occurrence of surface flooding and water logging.	The methodological approach was developed during the IMP study and applied in this thesis.

Table 3.10 cont.

- CHAPTER 4 -

FLOOD RISK AND MODELLING APPROACHES

4.1 Flood Risk Concepts

Chapter 3 demonstrated that the main physical constraint to economic development and social justice within the Salado Basin as a whole is the occurrence of frequent, extensive and long duration flooding events. In particular, the test area has one of the highest potentials for agricultural development, but this is constrained by the lack of a surface drainage network able to manage the excess runoff generated by groundwater-induced waterlogging and flooding situations. In general terms, the risks of flooding and waterlogging are a consequence of the interrelationship of various phenomena, including the:

(i) inherent complexities of physical processes.

(ii) spatial and temporal variability of the stresses on the basin, such as rainfall, evapotranspiration and actual evaporation: the latter expressed as a function of land use patterns),

(iii) often conflicting objectives of the multiple stakeholders in the basin, such as farmers, local authorities and federal and national agencies, and

(iv) fact that all deterministic estimates are based on a short period of record and an often incomplete and sparse database.

Bearing in mind the complexities outlined above, risk concepts and, therefore, risk management provide a useful framework within which to assess likely current and future scenarios, with and without water resources management and different forms of social intervention. MAFF (2000) exemplifies the objective of the framework and the concept of risk with the formulation of four questions:

(i) What might happen in the future?
(ii) What are the possible consequences and impacts?
(iii) How possible or likely are different consequences and impacts?
(iv) How can risks be managed?

Risk can be interpreted as the product of the chance (likelihood or probability) of a particular event occurring with the consequences (or impact) that would arise from its occurrence. Likelihood refers to the chance that a particular hazard occurs and hence, that a potential community could be exposed to a given harmful situation. Consequence should be interpreted as an undesirable consequence should the hazard event materialize.

It is important to highlight that risk encompasses multiple dimensions, from economic (such as physical damage to properties and infrastructure) to environmental and societal issues (such as disruption to natural habitats and distress to elderly people in the affected population). It should be noted that the spatial and temporal scales of the consequences do not have fixed boundaries attached to the extent and duration of a particular flood event: In agricultural and livestock activities, adverse effects extend beyond the duration of the flooding and the impact usually lasts much longer than the time necessary for soil moisture to return to normal levels. Under estimating any of the above aspects could lead to taking inadequate decisions and hence, inadequate expenditure of available resources.

To understand the different linkages between probability, hazards and consequences, and so assess potential mitigation measures, conceptual models of risk were developed, such as is the so called "source-pathway-receptor" model reproduced in Figure 4.1 and described below (ICE, 2001):

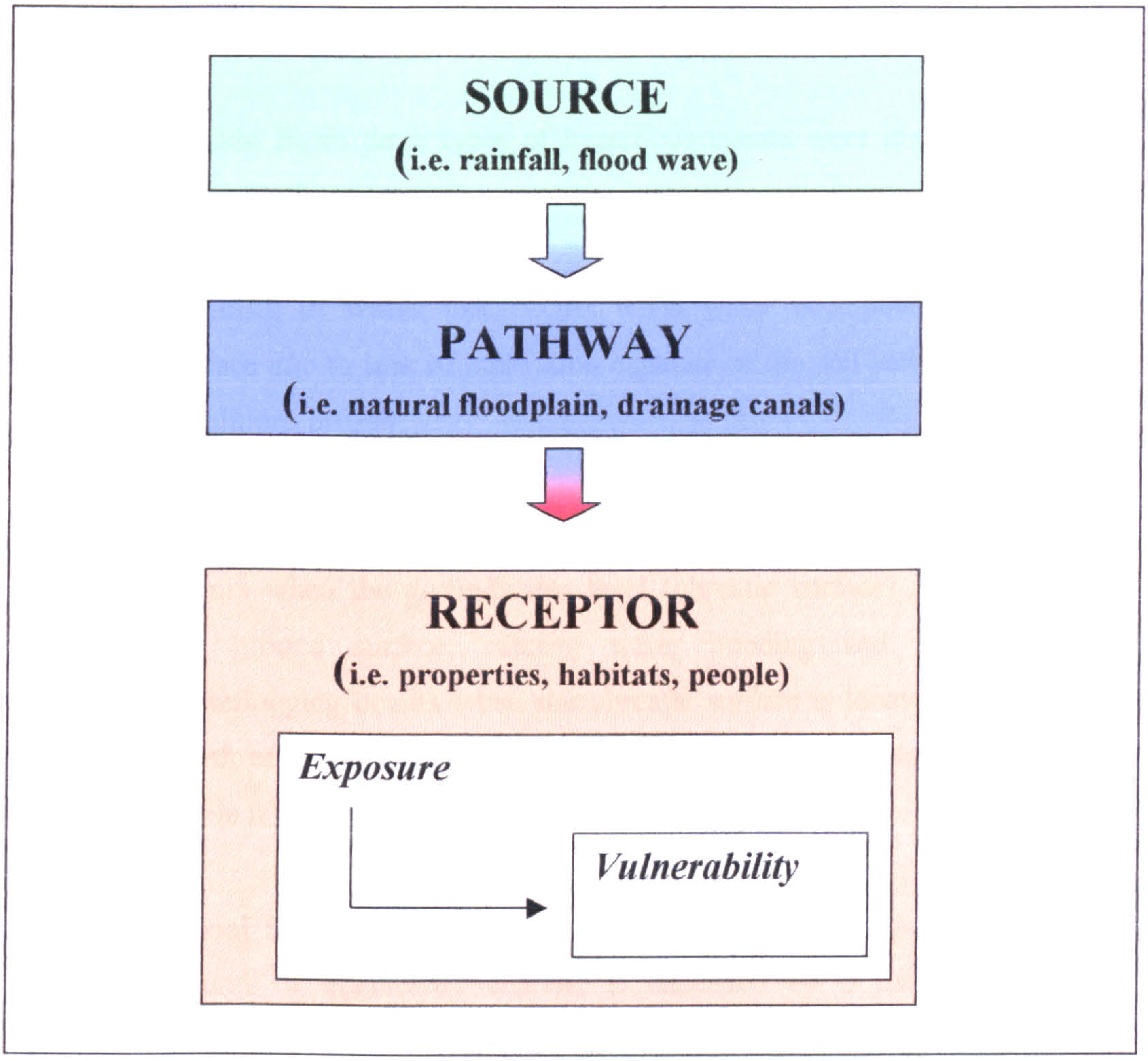


Figure 4.1: Conceptual Model of Risk, (modified from ICE, 2001).

In this study, the model was slightly modified to add the concepts of exposure and vulnerability in the relation to the receptors as the first step of assessment must begin by identifying all assets exposed and then determining what assets would be vulnerable to each particular hazard.

During a diagnostic study it is important to arrive at an accurate and homogeneous (catchment wide) representation of the regional hazards, exposures and, ultimately, risks. This also implies understanding the different weights of each of the blocks and linkages that form the conceptual model have in the final expression of risk for the basin. The conceptual model of risk also helps decision making on where mitigation measures should be targeted: While little can be usually done at the source level, flood defences are commonly a measure used at the pathway level and flood plain planning (to reduce exposure) usually fall under the receptor box.

Within the Salado Basin three types of hazardous events were identified and described in Chapter 3, as:

(i) **ponding of water** that occurs when water accumulates on the surface due to lack of infiltration capacity of the soil and flat terrain conditions prevail.

(ii) **groundwater-induced surface flooding or waterlogging,** that occurs when the groundwater level (phreatic surface) rises above the ground surface, causing water ponding and inundation. Waterlogging occurs when the phreatic surface is located within a depth of 50 to 70cm beneath the ground surface but does not rise above it.

(iii) **fluvial flooding** that occurs when the conveyance capacity of the natural or engineered channel is exceeded by a flood passing through the system and therefore, significant floodplain areas are inundated,

In the absence of a fluvial system in the test area, only the first two hazards are relevant; however the third is also cited as a risk analysis should encompass the entire basin and any drainage measure in the test area could increase the flow down the fluvial corridors and hence, increase that type of hazard.

Table 4.1 describes the different conceptual model of risk associated with the hazardous events presented above.

Ponding of Water	
Source	The prime source for this type of event are prolonged rainfall events that fall directly onto land characterised by soils of very low capacity for infiltration, which is worsened in areas where high water table conditions and low terrain gradients prevail.
Pathway	At the basin wide scale, the pathway is formed by numerous (mostly isolated) depressions in its downstream portion of the catchment (*Zona Deprimida*). In large rainfall events, water ponded in the depressions coalesces and the hazardous event is transferred to the river corridors (*Rio Salado*) as the impermeable area contributing to runoff increases. In the test area, the pathway is formed by the depressions behind parabolic dune crests that are characterised by having soils of low infiltration capacity due to the frequent accumulation of water.
Receptor	The receptor of this hazard is primarily linked to most livestock enterprises located in the *Zona Deprimida*: However, as the event evolves, the receptor also includes infrastructure along the river corridors of the cited area.
Groundwater Induced Waterlogging	
Source	The prime source for this event is direct rainfall rate that falls onto an area where the groundwater table is **just below** the land surface. Due to the relatively high infiltration capacity of the sandy soils that are prevalent in the test area and the low horizontal dynamics of the groundwater system, it may be argued that the infiltration rate to the soils and the groundwater heads themselves can be also termed a secondary source.
Pathway	This type of event affects, predominantly, all of the North West area of the basin, where a delicate balance between rainfall and evapotranspiration – coupled to the geomorphological characteristics of the area- maintains heads very close to the ground surface.

Table 4.1: Application of the Conceptual Model of Risk to each of the Flooding Mechanisms of the Basin.

Receptor	The main receptor of this hazard is the agricultural activity through: - salinization of soils due to the rise of phreatic levels with high content of salts, - physical limitations on the growth of crops during the initial stage after sowing, and - difficulty of accessing the farm during harvesting.
Groundwater-Induced Surface Flooding	
Source	The prime source for this event is direct rainfall that falls onto an area where the groundwater table is **above** the land surface.
Pathway	This type of event also affects, predominantly, all of the North West area of the basin where a drainage network has not yet been developed. Areas upstream of the parabolic dunes (the interdunal depressions) are the sites where groundwater first appears at the surface. This does not constitute a harmful situation on its own. However, when flooding depth increases sufficiently that certain micro relief thresholds are exceeded (i.e. water overtops the crest of parabolic dunes) surface water mobilises downstream along the interdunal depressions, creating substantial volumes of surface runoff and forming a significant pathway for the flooding mechanism.
Receptor	The receptors of this process are also the farming enterprises of the NW region as surface water affects: - livestock activities (unlike waterlogging), - farm infrastructure (such as fences) The appearance of water on the surface also implies the loss of crops, however, this is relatively small as cropping is not the main activity in these low lying areas within the region.

Table 4.1 cont.

Fluvial Flooding	
Source	The source is the cumulative drainage and overland contribution to the fluvial and canals network. The Salado basin does not have sufficient capacity to convey all of the annual surface runoff from the basin. The Rio Salado, and to some extent Canal 9, are the only major conveyors of water to the sea. The successive addition of drainage area to the Rio Salado Basin (Figure 3.2, Chapter 3) is being followed by a very slow natural evolution of the drainage network, which implies that out of bank flow situations will prevail for events of less than 2-year return period.
Pathway	Three physical areas can be identified as pathways for fluvial flooding: Active floodplains of the three main watercourses: Salado, Las Flores and Vallimanca, whose width and dynamics are very variable as described in Chapter 3. Relict floodplains and watercourses (mostly abandoned after heavy engineering works such as high level interceptors), such as the Gualicho-Zapallar-Camarones system that connects Canal 9 with the Rio Salado. Hill slopes that constitute the southern part of the basin and which transfer flood waters when the capacity of the streams that drain the hills is exceeded and large areas become overland flow routes.
Receptor	The receptor is largely restricted to settlements, isolated properties, farmlands and infrastructure located in the floodplains of the three main watercourses.

Table 4.1 cont.

Understanding risk, and defining adequate risk models, should be considered as the support for the delineation of the strategy for model development, as it allows identification of the different analytical components that ought to be included along with the required of coupling, so that the source and the pathway elements of risk can be adequately represented. In this respect, it is important to note the existence of interrelationships between the individual risk models at different scales of analysis. Figure 4.2 presents these interrelationships at the scale of a test area (either in the upstream or in the downstream part of the basin) and at the catchment scale.

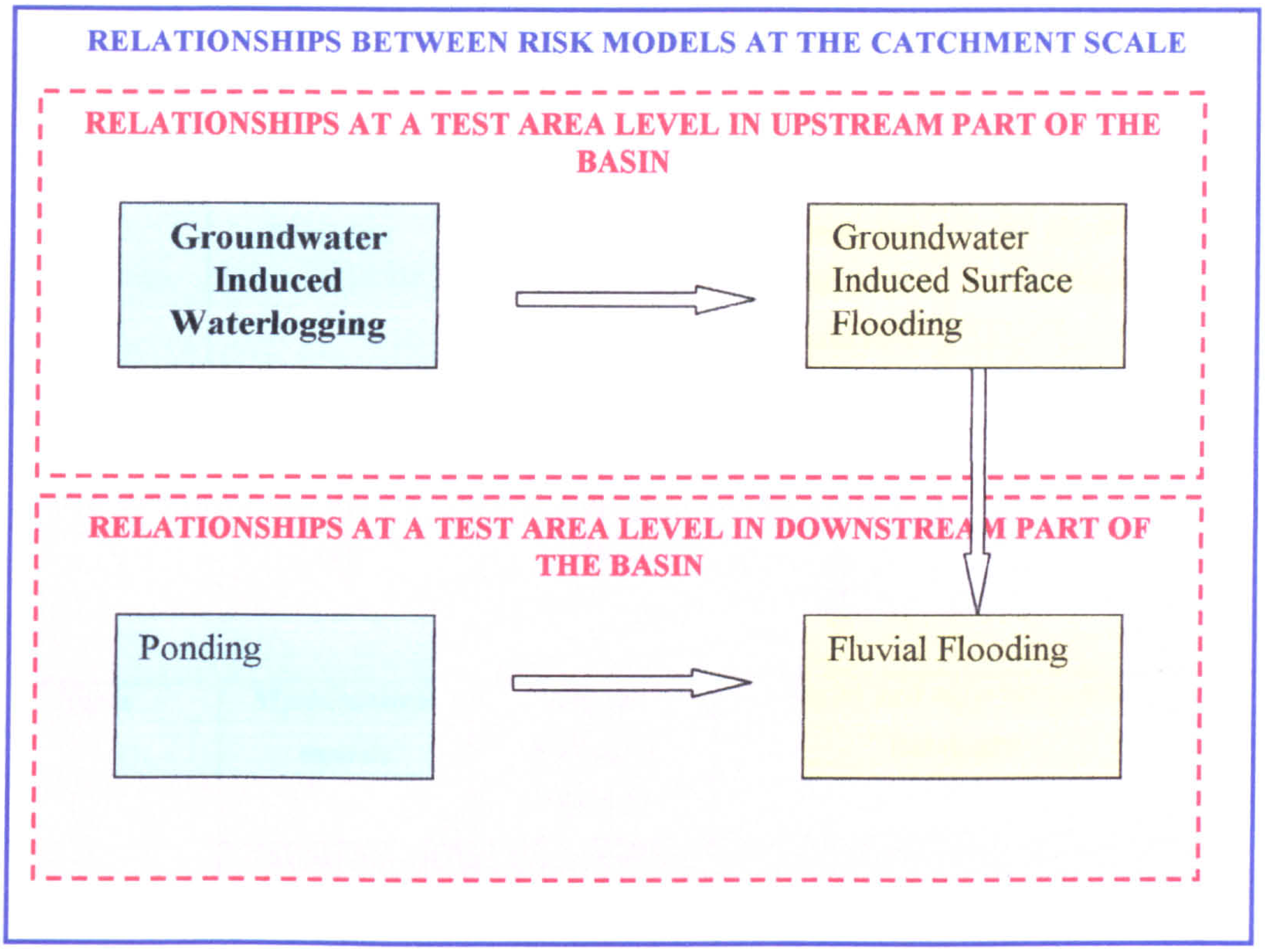


Figure 4.2: Interrelationship between risk models.

The next stage of the process should consist in the definition of a practical approach that conveys the concepts embedded in a model of risk for the basin into a practical assessment of current and future risk levels. A possible approach to adopt in order to estimate flood risk is summarised in Figure 4.3: In this figure, a parallel was set between the conceptual understanding of the processes that lead to flood risk, the tools required to arrive at a its estimation and the components of the risk model.

Processes	Climatic Stresses and Hydrological Processes	Geomorphic Setting and Hydraulic Infrastructure	Human Activities and Social, Environmental and Physical Infrastructure	Impact on social, environmental and physical capitals

(damage curves)

Tools	Mathematical models	Digital Elevation Model	Social and agro-economic databases
	Flood Probability Map (FPM)		Flood Risk Map (FRM)

Risk Elements	Source	Pathway	Receptor

Figure 4.3: Approach for the estimation of flood risk.

The two key outputs of the process are the Flood Probability and Flood Risk Maps (FPM and FRM). An FPM is a spatial representation of the probability of occurrence of an event of a given magnitude or higher. It is sometimes expressed in terms of the return period of an event of a given magnitude, i.e. the inverse of the probability of that event occurring in any one specified year. Two FPMs are relevant for the flooding processes throughout the entire Salado basin: the first represents the probability of occurrence of fluvial flooding and the second the occurrence of groundwater-induced surface flooding or waterlogging. As part of the IMP studies two independent set of FPMs were assembled. The FPM therefore yields, for every discrete element (raster element) of an area, the number of times during a specified period that the water level is expected to be above ground level (for fluvial flooding and groundwater-induced surface flooding) or just below it (for groundwater-induced waterlogging).

4.2 Flood Probability Maps (FPM) and Modelling Approaches

4.2.1 Conceptual Approaches

From Figure 4.3, it can be interpreted that the definition of a FPM encompasses the representation of the following elements:

(i) the spatial distribution of hydrometeorological stresses (rainfall, evapotranspiration),

(ii) the response of the physical environment (soil layer, aquifer, fluvial corridors) to the hydrometeorological stresses on the basin,

(iii) the spatial representation of flooding/no flooding (waterlogging/no waterlogging) situations in the basin (see Figure 4.4),

(iv) the calculation of the probability of occurrence of a particular event (flooding, waterlogging, fluvial flooding).

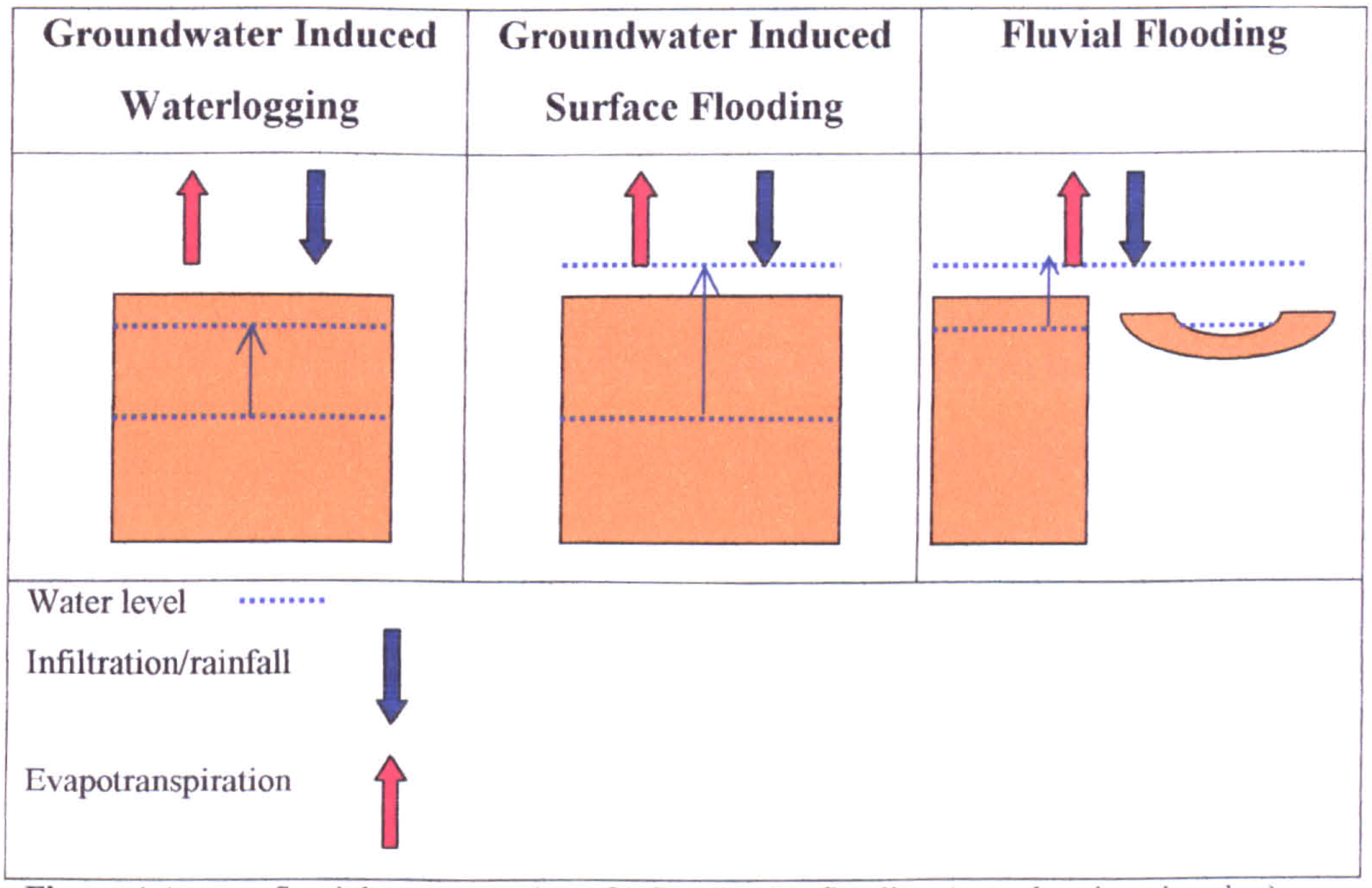


Figure 4.4: Spatial representation of a flooding/no flooding (waterlogging situation)

Mathematical models constitute a key tool to support the generation of FPMs; while the first element (point i) is a direct function of the availability of temporal and spatial records, the other three elements are functions of the modelling strategy adopted for the studies. The remaining part of this chapter therefore presents a conceptual discussion concerning the calculation underlying generation of FPMs, while Chapters 5, 6 and 7 present the results of applying different modelling approaches for GW and SW interaction.

The general statistical expression for the calculation of the frequency of occurrence of an event is:

$$Frequency_i = \frac{NoEvents}{(n+1)}$$

where,

i	= point in space for which the probability is calculated.
$NoEvents$	= total number of events in the period of analysis (n)

In terms of modelling, two approaches to calculating the probability of occurrence of an event can be identified, as follows:

<u>Approach I</u> $$F_{event} = \Phi[Frequency(Input)]$$

<u>Approach II</u> $$F_{event} = Frequency[\Phi(Input)]$$

where,

F_{event} = frequency of an event, for example the occurrence of groundwater-induced surface flooding, expressed as the number of times over a period that water is above the ground surface,

Input represents the driving hydrometeorological phenomenon, for example a flow hydrograph or a time series of rainfall, and

Φ represents the response function of the physical system to the hydrometeorological driver.

An example of the first approach is usually found in the representation of fluvial flooding, where the above expression translates into the following steps:

(i) statistical analysis of annual series of flow maxima to derive a time series (flow-time; rainfall-time) with different frequency of occurrence [***frequency(input)***],

(ii) execution of a mathematical model (i.e. a 1D river flow model) using the above inputs to estimate the response of the system in the form of predicted water levels along a river and its floodplain [*Φ(frequency(input))*],

(iii) calculation of the flood extent associated with the water levels for each return period (yielding the ***FPM***).

The second approach is most suitable for the representation of the occurrence of distributed events, as it is the case for groundwater-induced processes. In this case, the approach normally consists of the following steps:

(i) execution of a mathematical model (i.e. a hydrological rainfall-runoff model coupled to a 3D groundwater flow model) using time series of rainfall and evapotranspiration (*input*) to estimate the groundwater level for every simulated time step over the period of calculation (*n*). This results in the calculation of [*Φ(input)*],

(ii) calculation of the number of occurrences of a flood event, performing a calculation of a flood/no flood situation for every time step by comparing the groundwater level from the model with the level of the ground surface.

(iii) calculation of the flooding frequency as [***frequency(Φ(input))***].

Chapter 5 exemplifies the modelling approach carried out for the entire Salado basin to generate the FPMs for fluvial and the groundwater-induced surface flooding and shows sample FPMs, while Chapters 6 and 7 present an improved modelling method developed in this research project and evaluates its use for the generation of FPMs.

4.3 Further research issues

The previous section established the importance of risk analysis as part of the development of integrated catchment management plans and the vital role of mathematical models to support the process, in particular through generation of FPMs. Also, it emerged that the issue underlying the FPMs is clearly presence of GW-SW interaction. It follows that the accuracy of flood frequency of flooding will be directly linked, amongst other things, to how well GW-SW interaction is represented. Model development and FPMs therefore encompass a series of specific issues that are presented below and explored throughout the remaining chapters of this thesis.

For the entire basin, two different approaches were adopted to development of the FPMs of the IMP according to the type of flooding: approach I was adopted along the fluvial corridors (using a Regional Surface Water Model – RSWM) while approach II was chosen for the region where the test area is located (using a Regional Ground Water Model – RGWM). Therefore, two independent sets of FPMs were obtained (see Chapter 5), which were combined in order to produce an integrated expression for the entire basin. The combination of maps was carried out by overlaying fluvial probability maps, for 2, 5 and 10-year events, with the probability map for groundwater-induced flooding (or waterlogging). In areas where there was an overlap between the outcomes of both FPMs, the flood event with the higher probability of occurrence was selected. For example, if a cell (raster element) had a probability of flooding from the groundwater of 1in 5 years and a fluvial flooding probability of 1 in 2 years, the resulting combined probability assigned to that area was 1 in 2 years. Figure 4.5 summarises this methodological approach.

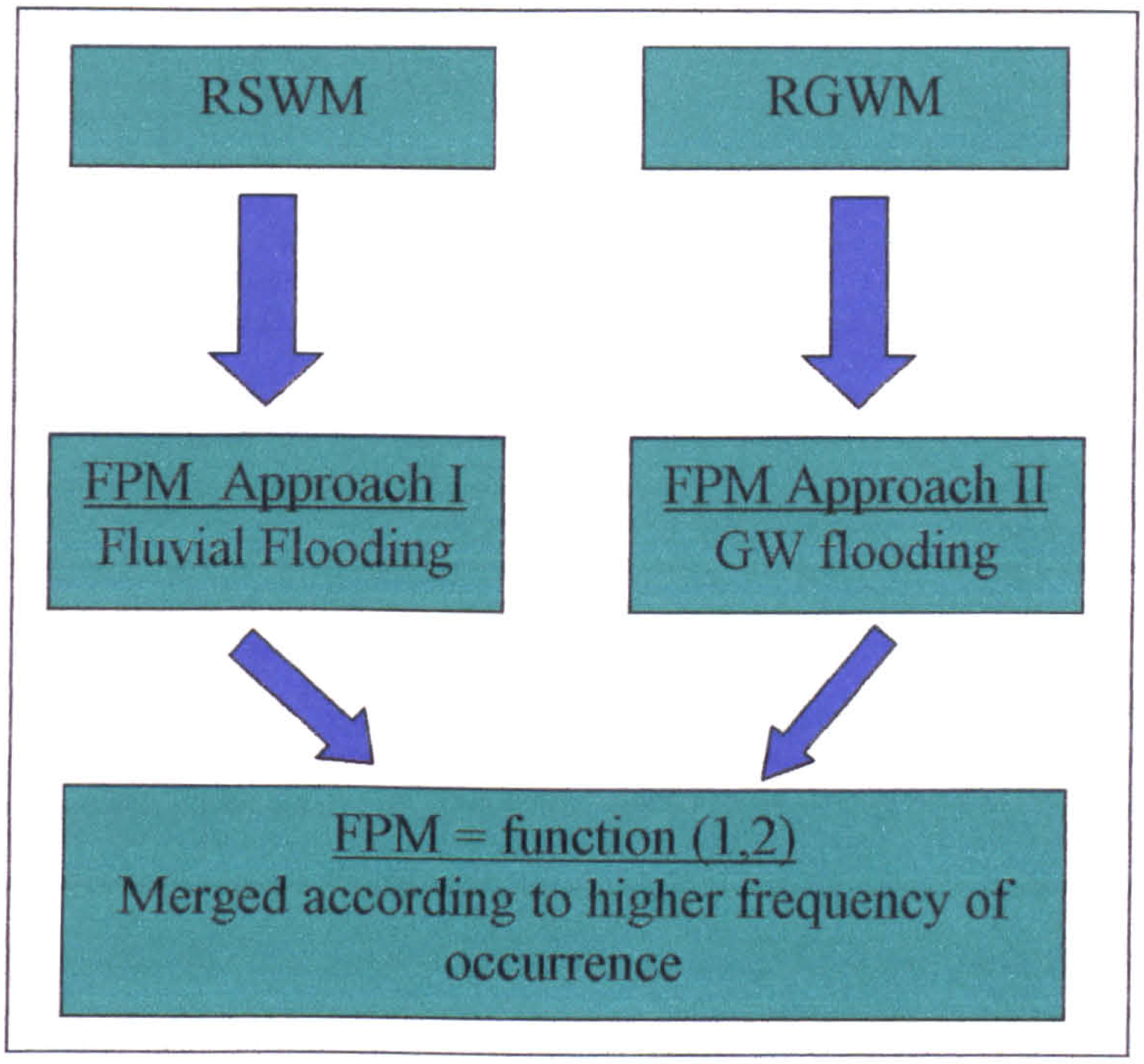


Figure 4.5: Methodology to calculate Regional FPMs.

The first research question that needs to be asked, before any further analysis of the generation of the FPMs, is *whether the models on their own bear a reasonable degree of approximation with the flooding mechanisms that drive the generation of hazards for the basin, and whether that level of approximation is compatible with the level of response required at the different stages of the planning process.*

The decoupled approach selected to calculate the FPMs is a direct consequence of the use of a modelling strategy that consisted of development of two, separate regional models (see Chapter 5). This was designed to suit the needs at a regional scale, but the research question arises as to whether it *would still be applicable to areas where there is a potential overlap between processes*? For example, along the fluvial corridors it can be argued that runoff-contributing areas are dynamic as a consequence of groundwater-induced flooding.

One of the premises for development of tools to support catchment management plans must be homogeneous treatment throughout the basin. This, for large catchment areas such as the Salado basin, can be an important issue that encompasses factors such as data availability, different geographies and worthiness of the adoption of complex modelling approaches. Also, another key element for consideration is the need to match modelling specifications to the requirements at various stages in a decision taking process. This triggers the question of *under what circumstances, the application of an integrated approach for fluvial and groundwater-induced flooding be required? What would this require in terms of modelling? Would this be applicable at a regional scale?*

A groundwater model was used to estimate groundwater-induced surface flooding (see Chapter 5); this implies that a comparison is made between the groundwater levels obtained from the RGWM and the ground surface at each point of the basin and the test area. *How well does the groundwater model handle representation of surface water processes? Is it sufficient for answering the question flood/no flood? How sensitive are the FPMs to a combination of different scales for representing the groundwater flow system and the ground surface?*

Calculation of frequency of occurrence has been carried out using a time series of annual maxima, which implies that so long as a flooding event occurs at any time during a year, that year is counted as a "year with flooding". This issue raises two questions: *is this the correct approach to support the subsequent economic analysis?* If so, *how sensitive are the different modelling approaches to the final outcome on an annual basis?*

The regional modelling strategy (presented in Chapter 5) adopted a simplified approach to representing drainage projects for the test area; basically drainage channels were not explicitly included in the model but the time series of infiltration entered into the aquifer model was modified to take account of the amount of water to be drained by the canals. This triggers several questions: *does the scope of the drainage system proposed, in terms of size, layout and density match the resolution of the RGWM? Can the RGWM serve the purpose* *of estimating the impact of the drainage scheme? Should an alternative approach be used?*

Different hydrological approaches were used to estimate drainage rates: such as the use of a tank model to simulate excess runoff from rainfall and the use of the continuous runoff series generated by the rainfall-runoff model; the latter under different hypothesis concerning soil parameters and different sets of rainfall stations. The time series for runoff were processed to obtain series of 1-month and 2-months maximums every year with which to estimate their frequency of occurrence. The outcome from the various approaches produced results that showed a significant disparity amongst them having had to adopt a single value for the designs carried out as part of the IMP. Table 4.2 shows the range of variation of the calculated drainage rate with different methodological approaches and the final value adopted in the IMP study.

Return Period (years)	Range of Estimated Values (mm/month)	Adopted value (mm/month)
2	12 - 27	17.5
5 [1]	20 - 44	30
10 [1]	25 - 65	45

Table 4.2: Drainage rates (mm/month) estimated in the IMP study.

[1] For 5 and 10-year return period the series of 2-month maximums was used.

In engineering terms, the use of these coefficients imply that the new drainage system will be designed to evacuate excess runoff at a constant rate (the drainage rate) during 1 month or 2 month periods, depending on the level of service adopted. This implies that, at some point, the channel capacity would be exceeded and water would have to stand back in the farms, but this is a reasonable and cost effective assumption in the design of drainage works to avoid investing in very large infrastructures. This approach also shows decoupling between calculation of the drainage rate and the analysis of its impact. Two questions arise: *can the drainage rates better be obtained by processing the results of an integrated GW-SW model that included the size and layouts of a proposed drainage scheme?*

All of the above questions bear a direct relationship with the adoption of a modelling strategy: However, the answers to the questions will depend on other factors, such as the objectives of the modelling approach, the stage in the planning process of the catchment, the scale of the problem and the period of analysis. Chapters 5, 6 and 7 discuss the various issues highlighted in this section through explanation and exploration of two different modelling approaches adopted. The first modelling approach is that I carried out during the IMP. The second is that developed as part of this research. Finally, Chapter 8 amalgamates the different issues and tries to answer the overarching questions concerning what to model and when to model it, through the development of a conceptual framework for modelling studies.

- CHAPTER 5 -

MODFLOW APPROACH

5.1 Background and Context

Chapter 3 established the importance of GW-SW interaction as one of dominant flooding mechanisms in the test area. Chapter 4 presented the risk models associated to the flooding processes, highlighting the importance of the relationship between the risk model representative for the test area (groundwater induced flooding) and the one for the fluvial corridors in the downstream parts of the basin. One of the conclusions obtained was that risk analysis has to be examined basin-wide in order to support strategic catchment management plans. Modelling, as the primary tool to support risk analysis (in particular in relation to the generation of FPMs) also has to address the peculiarities of different areas (such as those of the test area) but, at the same time, has to be able to achieve problem diagnosis and evaluation of options at the catchment level.

This chapter first presents the regional modelling strategy developed as part of the IMP studies, within which I performed a leading role in the actual development of its components, in particular the groundwater and surface water models. Description of the regional strategy is important in order to put into context the groundwater modelling of direct applicability to the test area. Following submission of the IMP, further analysis of the modelling approach was carried out as part of this research, leading to the questions and issues identified in Chapter 4. This Chapter explores the strengths and weaknesses of the approach adopted to modelling GW-SW interaction in the test area, but without losing sight of the basin-wide perspective, which is always required to progress to the ultimate outcome required: a master plan for the entire basin.

Chapters 6 and 7 follow this logic of analysis, but deal with the alternative approach proposed herein.

5.2 Regional Modelling Strategy

5.2.1 Objectives

The Terms of Reference of the IMP for the Rio Salado specified the need to develop three types of models as part of the studies without providing much guidance in terms of potential requirements for linkages between them. The specific models were:

(i) a rainfall-runoff model for all of the basin, to determine flow time series at different points in the catchment,

(ii) numerical or analytical models of the aquifers in different parts of the catchment to assess the existing and required drainage capacity of the area as a function of an acceptable flooding frequency, and

(iii) an operational model to simulate the surface water system, comprising, for example the main elements of the fluvial network, such as key river reaches, reservoirs, by-passes, lateral embankments and pumping stations.

This model specification reflects a clear perception by the Planning Agency (Ministry of Public Works) in terms of the need to use a quantitative and systematic approach to support decision-making with respect to water management in the basin. However, on its own this is insufficient to define a modelling strategy to be implemented. The next step should consist of the definition of the specific objectives of the tools to be developed, taking into account, for example, the three questions suggested by Gardiner (Gardiner, 1994): what is needed?, what can be provided? and what can be justified in terms of cost?

Even when formulation of the above questions seems trivial, Gardiner warns that, frequently, identification of what can be provided often changes the perception of need. This reinforces the idea of starting development of modelling strategies by analysing the objectives and needs of the disciplines involved before moving to discussion of the many tools that could be employed or which seem attractive when judged in terms of the number of components of the hydrological cycle that they can simulate. The issues of model availability and real needs are deepened by Anderson and Bates (2001), when they reflect that the proliferation of many models from commercial sources (some of them supported by government agencies) acts against the vulnerability of hydrological science.

5.2.2 Previous Modelling Experience in the Rio Salado Basin

The Rio Salado catchment has been studied on several occasions in the past, but in projects only focusing on parts of the region and not always covering all the disciplines relevant to integrated catchment studies. As a result, there have been various attempts to model parts of the region, trying to simulate the different processes that cause flooding in the province *(CFI, 1977; AyEE, 1988; Pedraza et al., 1992; IATASA, 1995)*. Each study employed "state of the art" modelling techniques available in Argentina at that time. Therefore in the first two cases considerable effort was put in developing the computational part of the model as well as setting it up. Also, in general, there was a clear awareness of the need to reproduce physical processes while taking into account the difficulties and complexities inherent to flatlands, which conventional hydrological techniques and models often fail to reproduce (Paoli, 1983; Prendres, 1983). However, a study performed in the Zona Deprimida (CFI, 1977) illustrates how overemphasising the simulation of physical processes (together with the lack of model technology and the inadequacy of the schematisation) can lead to failure of the modelling exercise. The work done in the Hinojo-Las Tunas lakes in the Northwest region (Pedraza et al, 1992; AyEE, 1988) is perhaps the closest representation to the flooding processes in the area, accounting for key features such as the inclusion of evaporation from the aquifer, the variation of ground saturation with time and the exfiltration of groundwater to the surface. However this model consists of two separate models, one for water balance at a cell level and one for the transfer of water between cells. The authors justified this approach on the basis of the distinct predominance in time of the two processes that occur in flatlands: a vertical balance at the beginning and horizontal transfers once ground saturation occurs and surface thresholds are exceeded. However this approach misses the connectivity and transfers that take place through the groundwater storage and it is not clearly expressed whether the water balance model is fed back by the volume of water between cells calculated by the transfer model. Overall, this model is a very valuable antecedent work for the area but it lacks versatility for its use in the generation of FPMs for baseline and project situations.

5.2.3 Strategy Adopted

A modelling strategy was set up with the aim of meeting the objectives and supplying the capabilities described in Section 5.2.1; but with two other fundamental premises:

(i) homogenous treatment covering the whole basin (170,000km^2),

(ii) suitability to run both event-based (up to 3-months duration) and long term scenarios (up to 100 years).

Three modelling packages were adopted to develop each of the models required in the study:

(i) HYSIM (Manley, 1993), a physically based, lumped, rainfall-runoff model. HYSIM is a deterministic model for continuous simulation that performs a water balance on a lumped basis, taking into account the most relevant processes that occur in the hydrological cycle, such as interception storage, evapotranspiration, surface and subsurface runoff, soil moisture content, recharge to groundwater and discharges to water courses.

(ii) MODFLOW: a code that resolves the equations for the 3D flow in a saturated porous media, through a finite difference scheme (Mc Donald and Harbaugh, 1988). The program deals with recharge and evapotranspiration as external fluxes, in the same way that deals with the external leakage to and from surface water bodies.

(iii) iSIS Flow: a one dimensional model that solves the Saint Venant equations for open channel flow for a mixed system of channels and hydraulic structures (Halcrow and HR Wallingford, 1995).

At the core of the modelling structure lies the GIS, which provides the platform used to process most of the input and output data used by the models. Finally, although not counted as a simulation tool, a Digital Elevation Model for the entire basin was constructed to provide basic topographic information to each of the models and, principally, to interact with the results (surface and groundwater levels) in order to derive flood extent and flood probability maps.

The tools developed in the study were coupled in order to simulate the hydrological processes and their linkages, across the basin. Table 5.1 summarises the inputs and outputs from the different models while Figure 5.1 shows their interaction schematically.

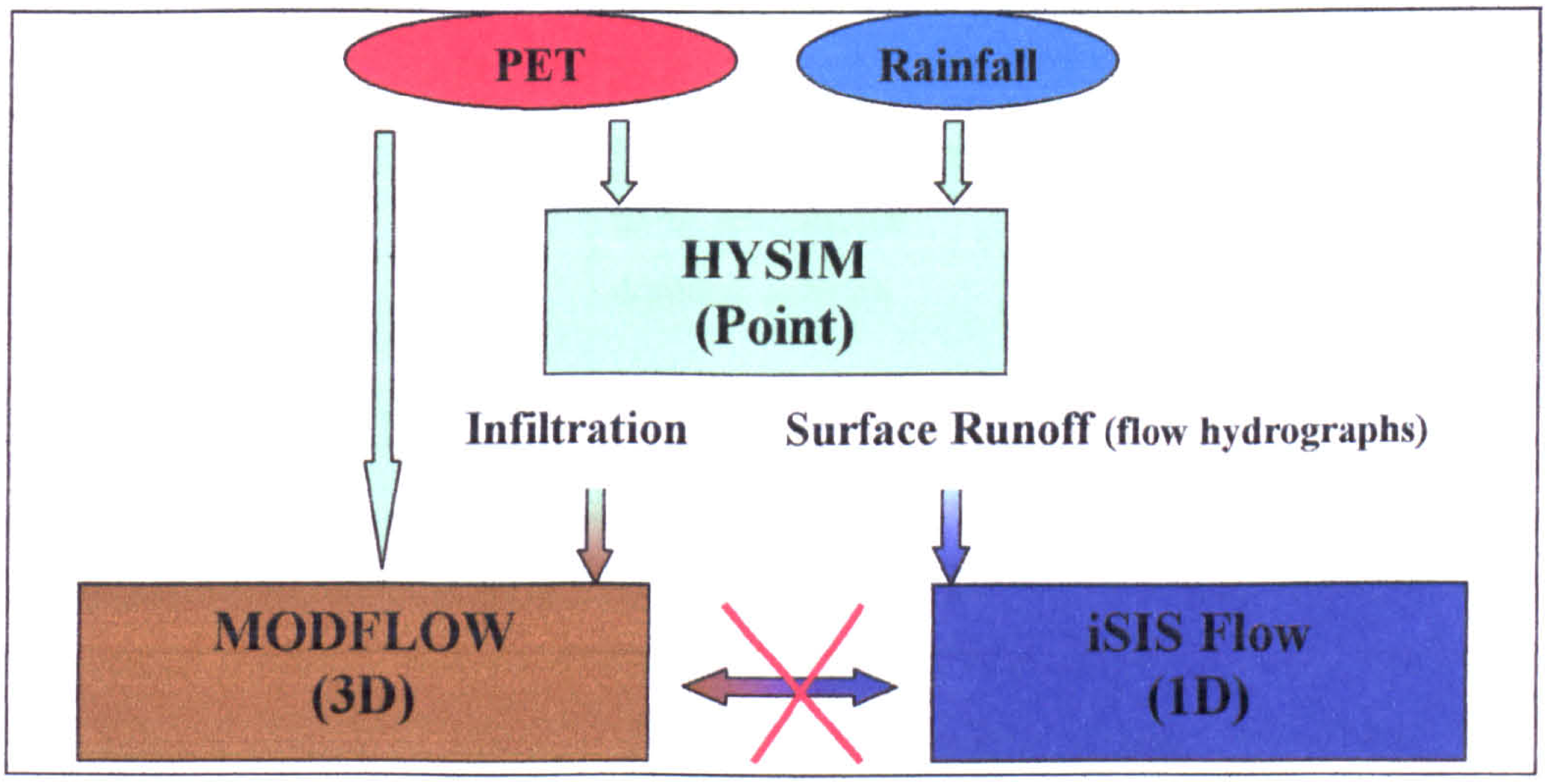


Figure 5.1: Schematic Representation of the interaction between the tools that form part of the Regional Modelling Strategy.

Model	Input	Output	Purpose
Ground Surface *DEM*	Topographic information.	Continuous representation of the ground surface on a raster basis (500m resolution).	Input to HYSIM to calculate main basin physical parameters. Input to MODFLOW for the internal calculation of ET as a function of GW levels. Input to iSIS and Modflow for calculating flood affectation maps.
Rainfall Runoff *HYSIM*	Time series of rainfall and evapotranspiration + catchment parameters	Time series of flow at the outlet of each subcachtment and time series of internal fluxes, such as infiltration to soil, recharge to aquifer, horizontal interflow between soil layers. Water balance per subcatchment.	Overall surface water balance. Infiltration/Recharge series to Modflow. Surface Runoff series to iSIS, in the form of upstream boundary conditions and lateral overland flow.
Aquifer *MODFLOW*	Time series of infiltration/recharge and evapotranspiration + aquifer parameters	Time series of groundwater heads.	Overal groundwater balance. Estimation of affected areas groundwater flooding.
Drainage System *iSIS Flow*	Time series of surface runoff.	Flow and Water Level Hydrographs at any point in the schematised drainage network.	Estimation of areas affected by fluvial flooding. Analysis of downstream impact of proposed upstream drainage measures.

Table 5.1: Input Stresses, Output and Purpose of each tool of the Modelling Strategy.

As described in Chapter 4, a modelling strategy has to be compatible with the conceptual model of risk established for the study area. Table 5.2 sets out how the regional modelling strategy dealt with the various components of the risk model for fluvial flooding and for groundwater-induced surface flooding and waterlogging.

Fluvial Flooding	
Element of the Conceptual Model of Risk	**Modelling Tool or Approach**
Source	Flood hydrographs (event based) of different return periods were derived using the rainfall-runoff model HYSIM and entered into the iSIS RSWM. The latter included a representation of the main conveyance and storage elements of the drainage system.
Source to Pathway	This linkage was represented within the RSWM by two elements: channel cross sections extended into the floodplain and transfer functions (spills or weirs) where the dynamics of floodplain flows differed significantly from the in-bank flows. In the first case, the transfer between in bank and floodplain flow is inherently represented by the topography of the extended section.
Pathway	Extended cross sections and flood cells were used to represent the out of bank conveyance and storage attributes of the system.
Pathway to Receptor	This was primarily represented by the DEM of the basin. Maximum water levels predicted by the RWSM at each of its nodes were entered into the GIS system to determine, based on the DEM, the extent and depth of flooding for each event.
Receptor	The receptors were accounted for by registering land use and regional cadastral information in the GIS system. This information employed frequency-damage curves to estimate the economic impact within the affected areas.

Table 5.2: The Relationship between the Regional Modelling Strategy and the Conceptual Model of Risk.

Groundwater Induced Surface Flooding and Waterlogging	
Source	Infiltration time series (on a monthly basis from 1963 to 1995) were derived from the HYSIM rainfall runoff model and entered into each cell of the MODFLOW RGWM.
Source to Pathway	This mechanism was represented by the groundwater heads computed in the RGWM on a cell by cell basis.
Pathway	The uppermost layer of the RGWM is represented as unconfined with infinite elevation. This means that there is no upper limit to how high groundwater levels can rise. Furthermore, there is no representation of the surface features (other than a small number of streams that do not in any case cause this type of flooding) and therefore the pathway is not explicitly represented by this strategy. Externally, the DEM was used to perform this function.
Pathway to Receptor	The GIS was used to process all (monthly) groundwater heads and compared them with the DEM in order to detect which cells were flooded and which waterlogged, depending on the relative position of the groundwater head to the ground surface.
Receptor	As per the approach adopted for the fluvial flooding.

Table 5.2 cont.

5.2.4 Regional Digital Elevation Model (DEM)

As part of the IMP studies, a DEM was constructed for the entire basin using a triangulation-based (TIN) ground model derived from 1.25 and 2.5m interval contours and spot heights (on average, 1 about every 3km^2) digitised from 1:50,000 IGM maps (Ordinance Survey Maps of Argentina). In areas with steep gradients (in the south of the basin) the contour interval was 5m and the maps used were at a 1:100,000 scale. To obtain an accurate representation of micro-surface features in the plain, each wetland area (identified using satellite imagery) was given an elevation based, where available, on observed water levels from the AyEE study (1990). The area is predominantly flat and the topographic data sparse, so the interpolation procedure used "forced" the edges of the triangles to coincide with either drainage features (primarily water courses) or digitised contour lines. This guaranteed that the previous topographic interpretation available from the survey maps was preserved and used in a meaningful way.

As most of the spatial applications are based on a raster analysis, the TIN-based DEM was converted to a raster grid of 500m resolution by linear interpolation from each of the triangles. Other grid resolutions were tested (100m and 1000m) but 500m resulted to be an optimum value that balanced the following factors: density of source data points, need to capture micro-relief features (i.e. crest dunes are separated 5km approximately) and post-processing efficiency. This last point is important as the resolution of the DEM drives the resolution of the final FPMs when combined with all raster-based post-processing. Figure 5.2 shows a mosaic of information obtained from the DEM, such as regional contours at 5m intervals, a hill shading view, and a 3D representation of micro-surface features, such as the parabolic dunes.

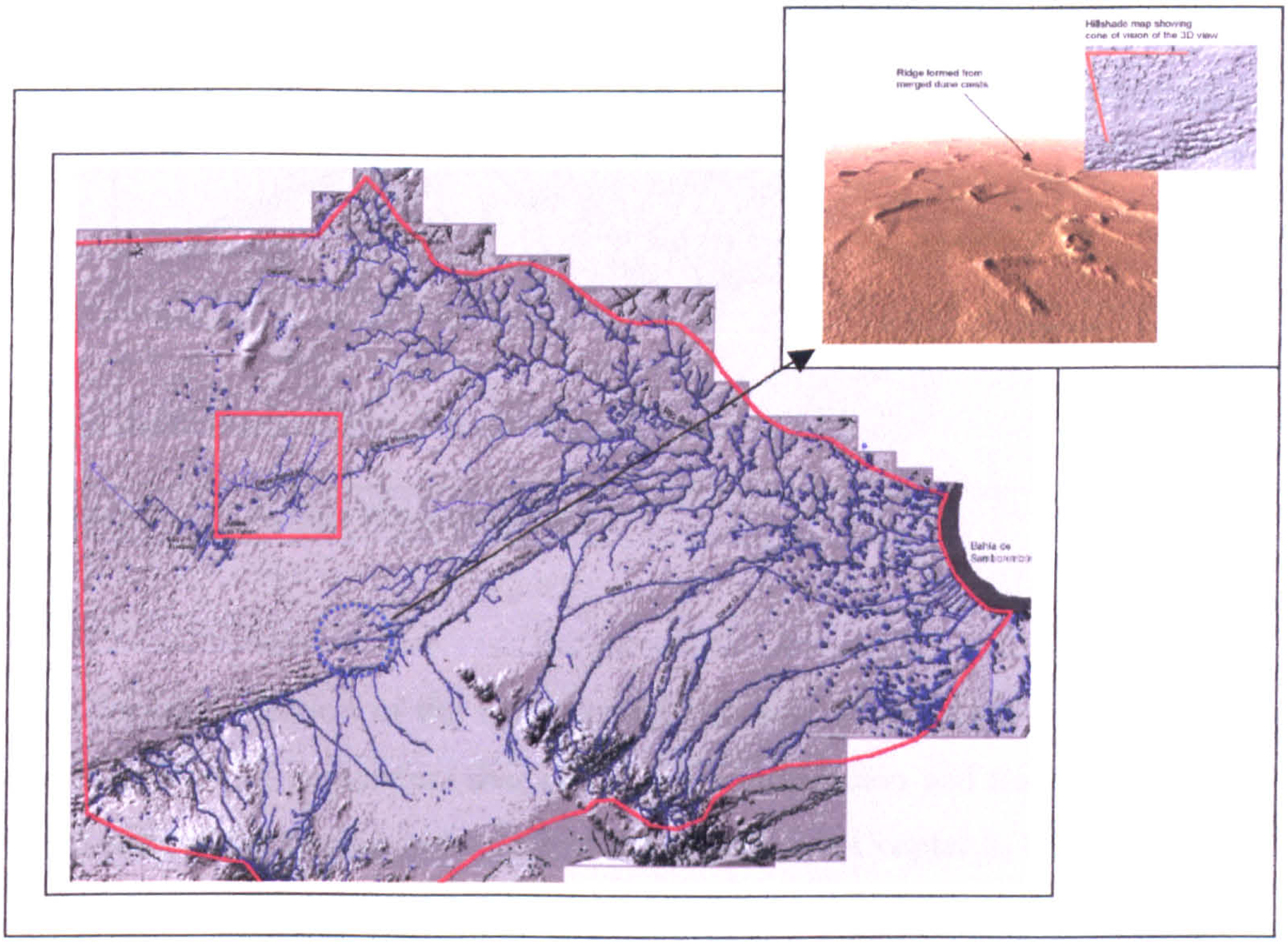


Figure 5.2: Digital Elevation Model

5.2.5 Regional Rainfall-Runoff Model (HYSIM)

The basin was schematised into 25 surface water sub-catchments, delineated to match topographical divisions and gauging station locations in the river drainage system. An exception was made in the region where the test area is located, where no surface drainage system exists, and there are no permanent gauging stations in the existing canal system that runs across that region. Figure 5.3 shows the location of each of the hydrological sub-basins.

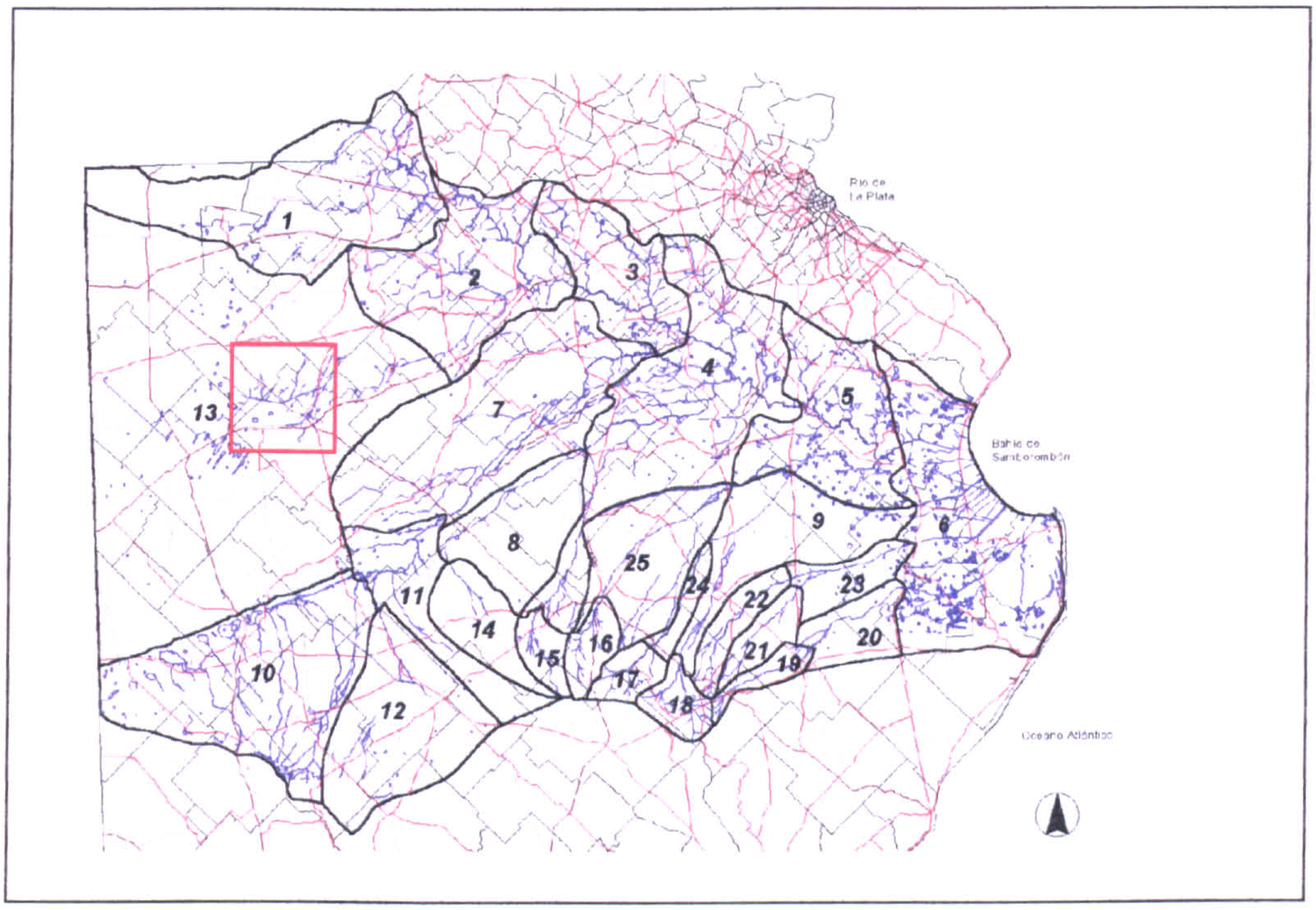


Figure 5.3: Surface Water sub basins.

The conceptualisation of the hydrological response of the basin is provided by entering a set of parameters that define the accumulation and transfer of water from each of the storage units defined in HYSIM (see Chapter 2, Figure 2.4):

Interception storage: this represents the storage at an above ground level, which is filled from rainfall and subject to evaporation from open surfaces.

Impermeable area: the moisture in excess of interception that falls in this portion of the catchment contributes directly as runoff to channels.

Upper soil horizon: this represents storage in the top layer of the soil. Storage is controlled by the potential infiltration rate, evapotranspiration, soil parameters, and rates for horizontal and vertical moisture transfers.

Lower soil horizon: as above but representing deeper soil layers, still subject to evapotranspiration.

Groundwater storage is represented by two infinite linear reservoirs; the first called transitional groundwater designed to represent moisture held in fissures that would contribute to channels rather to recharge to the deeper saturated aquifer.

All lateral flow contributions are finally routed (Minor channels) to a receiving watercourse using an instantaneous unit hydrograph. Finally hydraulic routing in rivers is carried out adopting the kinematic wave approximation.

The key parameters used in HYSIM are:

Total available soil moisture (mm) and proportion of that within the upper soil horizon (%). The former is calculated as a function of rooting depth, porosity and wilting point.

Saturated permeability (mm/hr) at various soil horizons. These control the vertical movement of water between soil layers and from soil to groundwater storage.

Interflow runoff factors at various horizons (mm/hr). These control the horizontal contribution to catchment runoff that goes to minor channels first and ultimately to the receiving watercourses.

Groundwater discharge coefficients (1/hr). These parameters control the transfer of water out of each of the groundwater storages to watercourses.

The following Table 5.3 provides a summary of representative parameters used in HYSIM across the basin.

Parameter	**Representative value**
Time to peak to route runoff to final watercourse (hr)	48-500
Rooting depth (mm)	800-1100
Proportion of upper to total soil horizon (%)	0.3
Porosity (-)	0.45
Impermeability (mm)	0.01
Interception (mm)	2
Permeability between upper and lower horizons (mm/hr)	0.1-15
Permeability between lower soil horizon and groundwater (mm/hr)	0.1-2
Interflow – Upper soil horizon (mm/hr)	0.01-2
Interflow – Lower soil horizon (mm/hr)	0.001-1.5

Table 5.3: Representative HYSIM parameters for the basin.

The main data requirement for HYSIM is the input of meteorological data such as rainfall and the potential rate of evapotranspiration. Both data sets were entered in the form of daily time series after a careful check for consistency and infilling of data, as the hydro-climatic database available was characterised by having an important number of stations available but a very discontinuous record. Weighted averages were used to convert each point rainfall time series into an areal value to be applied in each sub-catchment: Stations located within a radius of 25km were used to obtain the areal rainfall, whereas climatic stations located up to 50km away were used for estimating the potential evapotranspiration. Approximately over 100 rainfall stations and 15 climatic stations were used to characterize the entire study basin. However it is important to note that, for the period after 1987, only data for 11 rainfall stations was available. The main source of data to estimate hydrological parameters for the terrestrial portion of the cycle was an available soil database, which was entered into the GIS to facilitate interpretation and extraction of values. The remainder of the required parameters were extracted from the reports output by previous studies and the existing cartographic database.

The response of the system is characterised by time series of flows recorded at the gauging stations at the outlets of the sub-catchments. These data sets usually come in one of two forms: either as isolated, gauged flows (for example on a monthly basis in the Salado region) or as daily flows converted from a water level chart recorder using a rating curve. The flow data are not required for simulations of the model, but they are required for its calibration. The calibration process of the rainfall-runoff model involves matching, within a tolerable (and practical) limit, the simulated flows at the catchment outlet to the ones observed in nature. Two calibration exercises were carried out: a long-term, base calibration, and an event based calibration. The first calibration exercise aimed at producing long-term series which preserved, in a statistical sense, the key descriptors of the observed series (such as, the mean and the standard deviation). This involves achieving an adequate representation of the average response of the catchment to rainfall, in order to feed other long term regional models, as described in a later section. The event based calibration aimed at achieving a close representation of the peak flows associated with selected flood events.

The continuous simulation of the rainfall-runoff model was performed using a daily timestep for a period of 36 years, from 1959 and 1995. The limits of the period were determined by the availability of good records of data. An earlier start date than 1959 was precluded by the availability of climatic data, while an end date of 1995 was determined by the availability of rainfall data. The main outputs from the HYSIM model were:

(i) water balance for each of the sub-catchments,

(ii) infiltration time series (daily and monthly) to feed the Regional Groundwater Model,

(iii) upstream flow boundaries and lateral inflows to rivers and channels, represented in the hydrodynamic model.

Table 5.4 presents a summary of the water balance results from the model for two representative areas: one within the fluvial corridor of the Rio Salado and the other located within the area dominated by the fields of dunes. The latter coincides with the location of the test area. Values are expressed in mm and are the average response of each area for the period 1959-1996.

Component of the hydrological cycle	Area in fluvial corridor	Area in field of dunes (Test Area)
Rainfall	875	921
Potential Evapotranspiration Rate	1036	1167
Actual Evapotranspiration	818	882
Infiltration	554	534
Lateral flow	41	15
Recharge (includes "transitional and groundwater storages")	58	23
Baseflow	4	0
Surface Runoff	12	24

Table 5.4: Summary of the water balance as predicted by HYSIM (values in blue show the closure of the balance)

The above figures confirm the predominance of the vertical balance, with surface runoff less than 5% of rainfall, actual evapotranspiration 80% of the full potential rate, and infiltration more than 60% of rainfall. However the water balance for the dune field area predicts a value for surface runoff and lateral sub surface flow that does not correspond to the physical situation of that area that lacks from a drainage network and water ponds in the surface until is consumed by evaporation. Recharge values are also very small and do not agree with the observed pattern of groundwater level fluctuations.

5.2.6 Regional Groundwater Model (MODFLOW)

MODFLOW was used to construct the Regional Groundwater Model (RGWM) for the entire study area, using a 5km by 5km, grid. Three layers in the vertical were required to represent the main hydrogeological formations of the aquifer. Each layer was split into three geographical zones with potentially different hydrogeological properties. The location of the three zones is shown on Figure 5.4 and the properties of zones in each layer are summarised in Table 5.5. Three-dimensional surfaces representing the interfaces between the layers were generated using GIS tools in order to define the thickness of the hydrogeological formations in every MODFLOW cell.

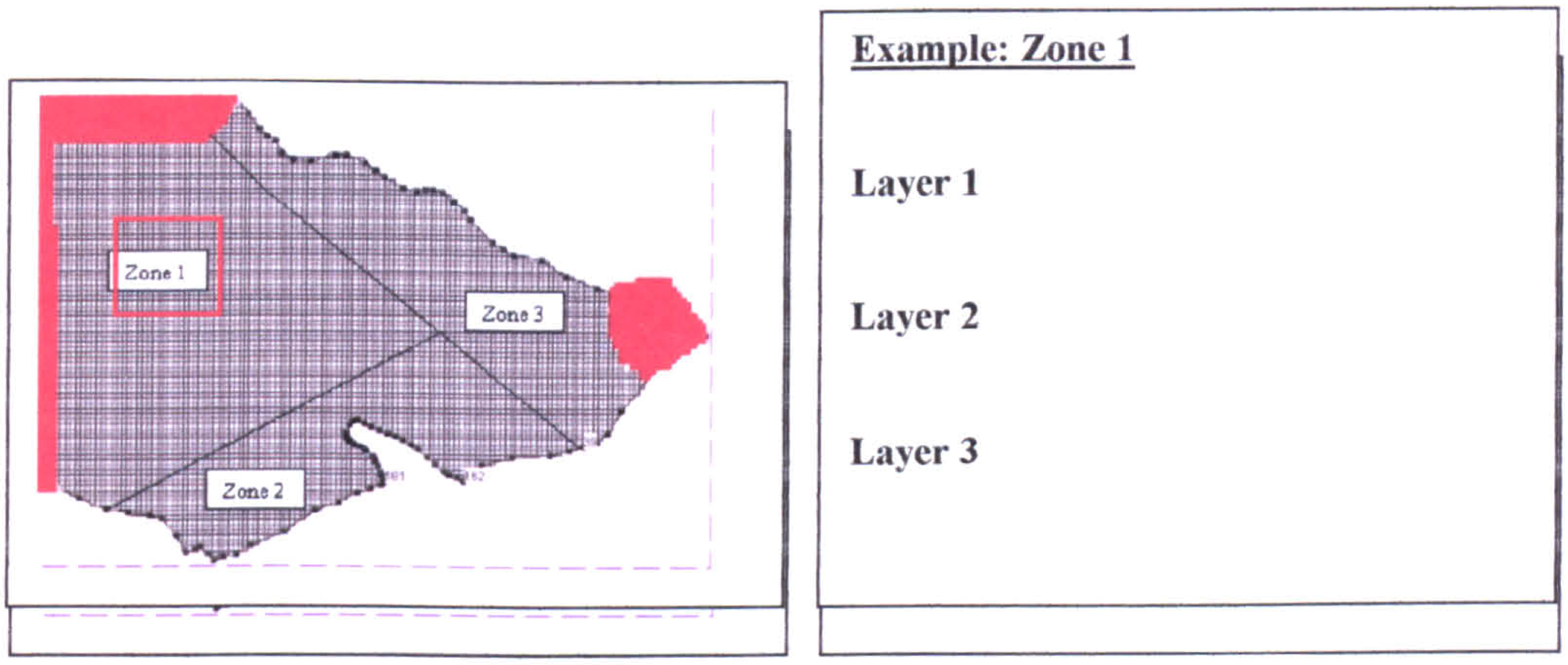


Figure 5.4: Hydrogeological zones included in the model. In red, the active cells outside the project area are shown. The red box indicates the location of the test area in relation to the catchment wide model.

Layer	**Formation**		
	Zone 1	**Zone 2**	**Zone 3**
1	Sand dunes	Pampeano	Pampeano
2	Pampeano	Pampeano	Pampeano
3	Araucana	Pampeano	Puelche

Table 5.5: Hydrogeological formations in each layer of the model. See Chapter 3 for a description of each lithology. Zone 1 corresponds to the formations of the test area.

The northern and southern boundaries of the basin are groundwater divides and so were defined in the MODFLOW model as no-flow boundaries. In the west, fixed heads have been set at between 70km and 80 km to the west of the provincial border to facilitate possible flow across the boundary. The eastern boundary is the sea and is, therefore, also a fixed head boundary. With fixed head boundaries at both ends of the flow system there is the possibility that heads could be artificially constrained within the model area. However, as the area is so large, in practice, such effects proved to be insignificant. Figure 5.5 presents a view of the schematic of the MODFLOW model.

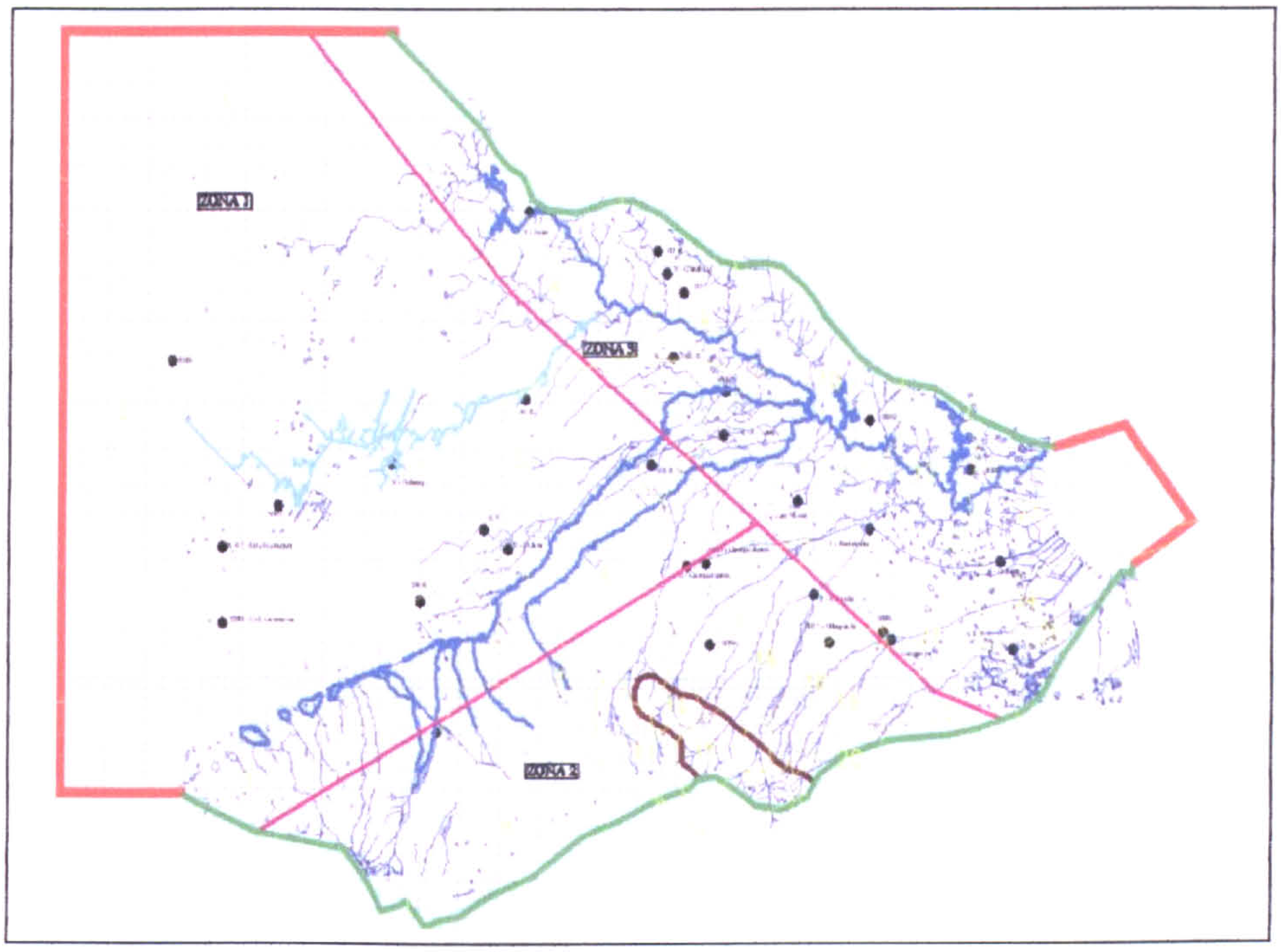


Figure 5.5: Schematic of Regional Groundwater Model (MODFLOW).

In the hydrological cycle for lowland plains, the balance between recharge and evapotranspiration directly from the water table is an important feature. The MODFLOW recharge and evaportranspiration packages have been used to simulate the vertical gains and losses of water to the aquifer. The inputs to the RGWM were the infiltration and evapotranspiration time series (processed to obtain monthly values) obtained from each of the sub-catchments of the basin. Kriging was used to fit a continuous surface to the infiltration and evapotranspiration values calculated for each time step (a month); which were sampled at a 5km interval to provide spatially and temporally varying data to MODFLOW. The approach taken to simulate evapotranspiration (ET) in MODFLOW is based on the following assumptions: when the water table is at or above ground level then ET losses occur at the potential rate (PET); when the depth of the water table below ground level exceeds a certain interval (termed the ET extinction depth; for which a value of 3m was adopted), ET losses cease; and between these limits, evapotranspiration varies linearly with water table elevation.

However, during development of the IMP, this module of MODFLOW was found to be inadequate to simulate rising trends in the groundwater heads and I modified the original code to suit the needs of the project. MODFLOW, developed to simulate the flow of water in the saturated porous media, expects a recharge time series as a normal input; this implies infiltration to the uppermost soil layer net of evapotranspiration from the unsaturated zone and of horizontal interflow. Because of the inability of parameterised rainfall runoff model developed with HYSIM to predict the correct recharge time series, it was decided to use the infiltration and simulate the evaporative losses in MODFLOW. Two issues arise from this approach:

(i) the coupled HYSIM-MODFLOW model does not simulate evaporative losses in the unsaturated zone as evapotranspiration, in MODFLOW, is only a function of the position of the water table. This can be a reasonable approximation when the water table position oscillates seasonally within a small depth below the ground surface,

(ii) all of the Northwest region (including the test area), had a period prior to 1970 with heads well below ground surface. Using infiltration, net of losses in the unsaturated zone, and the original module of MODFLOW would cause a sudden rise of the groundwater levels and the inability to represent the spread of time over which the rising trend took place. I then modified MODFLOW to account for a spatially variable evaporative loss when the aquifer levels are below the extinction depth. Figure 5.6 exemplifies the functioning of both, the original and modified ET module of MODFLOW. When the depth to the water table is greater than the extinction depth, the program multiplies the full potential evapotranspiration rate by a factor to account for a loss in the unsaturated zone. This factor is constant in time but can vary spatially, on a cell-by-cell basis. Despite this approach permitted to reproduce adequately the rising groundwater trend reported in the Northwest region, the abrupt change in the calculation between the unsaturated and the saturated zone can generate a sudden increase in level as they pass from one zone to the other. This could be overcome by defining a transition zone over which evapotranspiration should vary without abrupt changes (see dashed red line in Figure 5.6).

A modified and enhanced version of the ET package was subsequently developed for MODFLOW 2000 (Banta, 2000) that permits to use a segmented function for the calculation of the evapotranspiration, but it would still be inadequate for the same reasons expressed above.

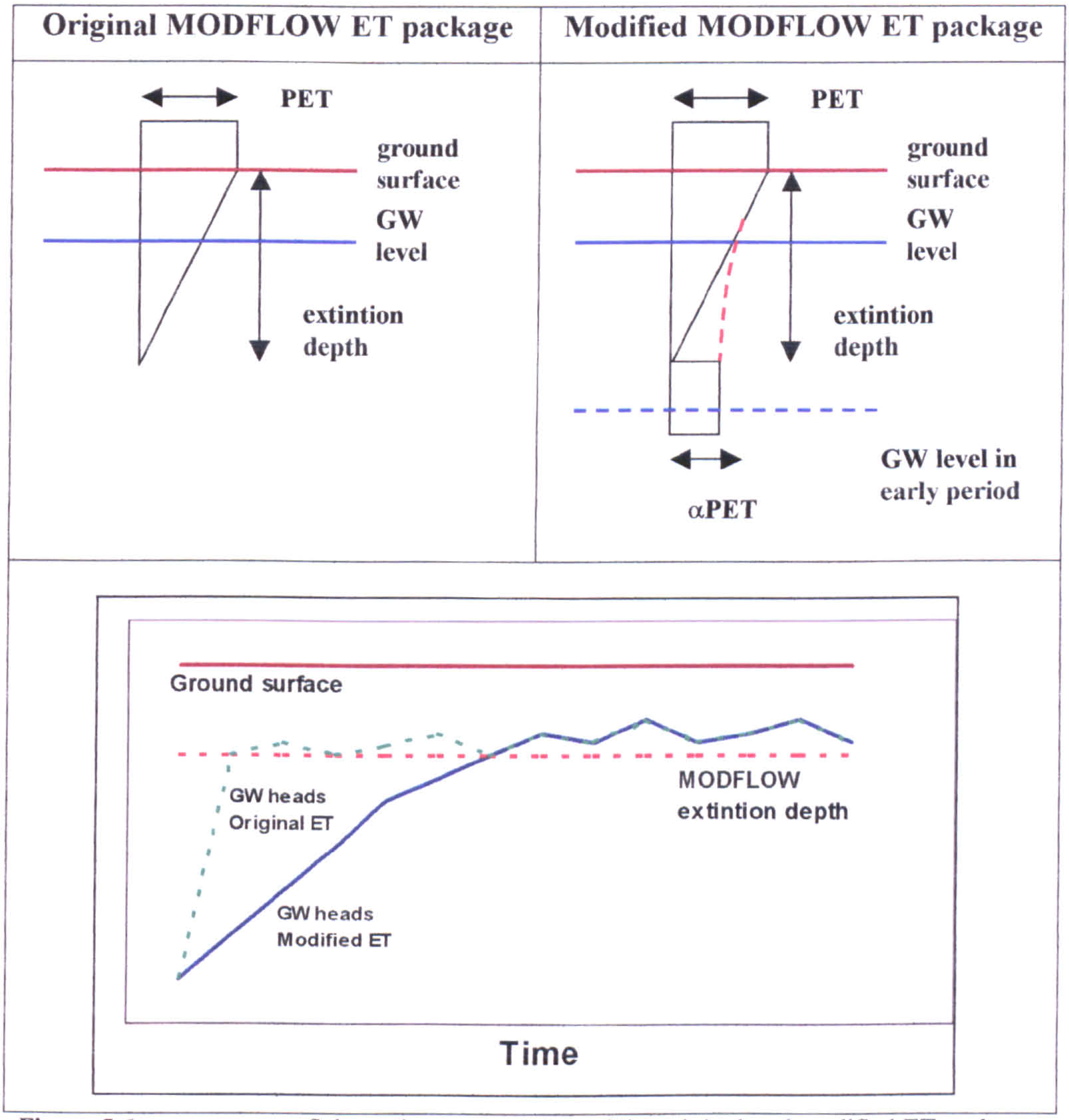


Figure 5.6: Schematic representation of the original and modified ET packages of MODFLOW

For calibration purposes the model was run for a data-constrained calibration period of 33 years (1963-1995) starting in January 1963, with a stress period of a month (30.44 days); the latter defined as the period over which 'stresses' on the aquifer, such as recharge and ET, are considered constant. The objective of model calibration was to adjust certain model parameters to obtain a good match between simulated and observed variables. With a physically-based modelling system such as MODFLOW it is important that adjusted model parameters remain within a physically realistic range. In addition, and bearing in mind the regional scope of the model, parameters should not be adjusted individually at each cell simply to improve the match between observed and simulated values unless there is additional information to confirm the variations. It must be accepted that "perfect" matches are not possible (nor should be expected) if only spatially uniform data can be applied in a model and dominate the model results. In all models compromises are necessary, but they have to be hydrogeologically plausible. Near "perfect" matches must be treated with some suspicion, as they are suggestive of data manipulation solely with a view to producing a fit of model results to observed data. To judge the acceptability of a model calibration, taking account of the database shortcomings, the limitations of the model used and the compromises adopted, the following characteristics are normally evaluated:

(i) agreement between modelled and observed groundwater head distributions (based on interpretation of observed heads),

(ii) agreement between modelled and observed transient head distributions,

(iii) modelled heads being within about +/-2m elevation of the recorded heads at individual observation boreholes, and

(iv) a comparative range in hydrograph amplitude between an individual borehole hydrograph and a corresponding model hydrograph.

The main source of data used to calibrate the RGWM model was a set of 28 groundwater observation wells, chosen to provide as good a spatial variation over the period 1963 to 1995 as it was possible given the availability of data. Problems were encountered in determining the precise locations of the wells. Most locations were confirmed through map checking, with all wells confidently located within 1km. This is acceptable for most of the basin, where water levels only change by only about 1m in 1km.

In groundwater modelling, where feasible, emphasis is normally placed on calibration against known flows such as dependable river base flows, spring flows and recorded well abstractions. Such data were not readily available for the basin and, while flows are obviously important, the groundwater-flooding phenomenon is essentially a consequence of head rise, so that head calibration in the context of the regional model assumes a somewhat unusual prominence. In using the hydrograph data for calibration it has to be accepted that they may have been variably liable to a number of influences that have given rise to errors. For example: ground elevation at the observation borehole may not be accurately known, measurements may be recorded from a point at the well head that is not accurately related to the relevant elevation datum, heads in an observation borehole can be influenced by drawdown responses induced by nearby abstraction wells and by penetration through various hydraulic layers in a layered system. Although errors are inherent in all hydrographic data it is important to note that the observation borehole levels represent point data, while the comparative regional model hydrograph reflects an averaged cell head over an area of 25km². With such a disparity, it is inevitable that differences between observed and modelled heads occur. Figure 5.7 shows, for three key locations, the comparison between observed and modelled groundwater levels. These locations were selected to typify the response of the groundwater flow system across the basin: Junín is located in the northern part of the basin close to the fluvial corridor of the Río Salado and, with a fairly good coverage of data, depicted the rising groundwater trend in the area; Pejuajó lies well at the core of the dune field area where the test area lies and was also subject of a clearly manifested rising trend; finally Chascomús is a typical location of the Zona Deprimida where no variations in levels are expected due to the close control of the sea level. The results obtained proved that the model was able to reproduce satisfactorily the existing seasonal level variation close to the ground surface and also the ascending trend in the Northwest as a consequence of the increase annual rainfall recorded in the area since 1960/1970, with differences between observed and predicted heads mostly less than 1m. The model also showed good agreement between the groundwater head distributions for 1974 and 1988 with those derived from interpretation of observed data. This proves that the model was also able to reproduce the groundwater gradients throughout the basin, implying a good control on groundwater flows. Figure 5.7 also compares observed and simulated levels for 1988: This particular agreement indicates that the increase in groundwater storage that occurred during the 1970s and 1980s was satisfactorily reproduced not only on a point by point basis (i.e. for the observed hydrographs) but also regionally.

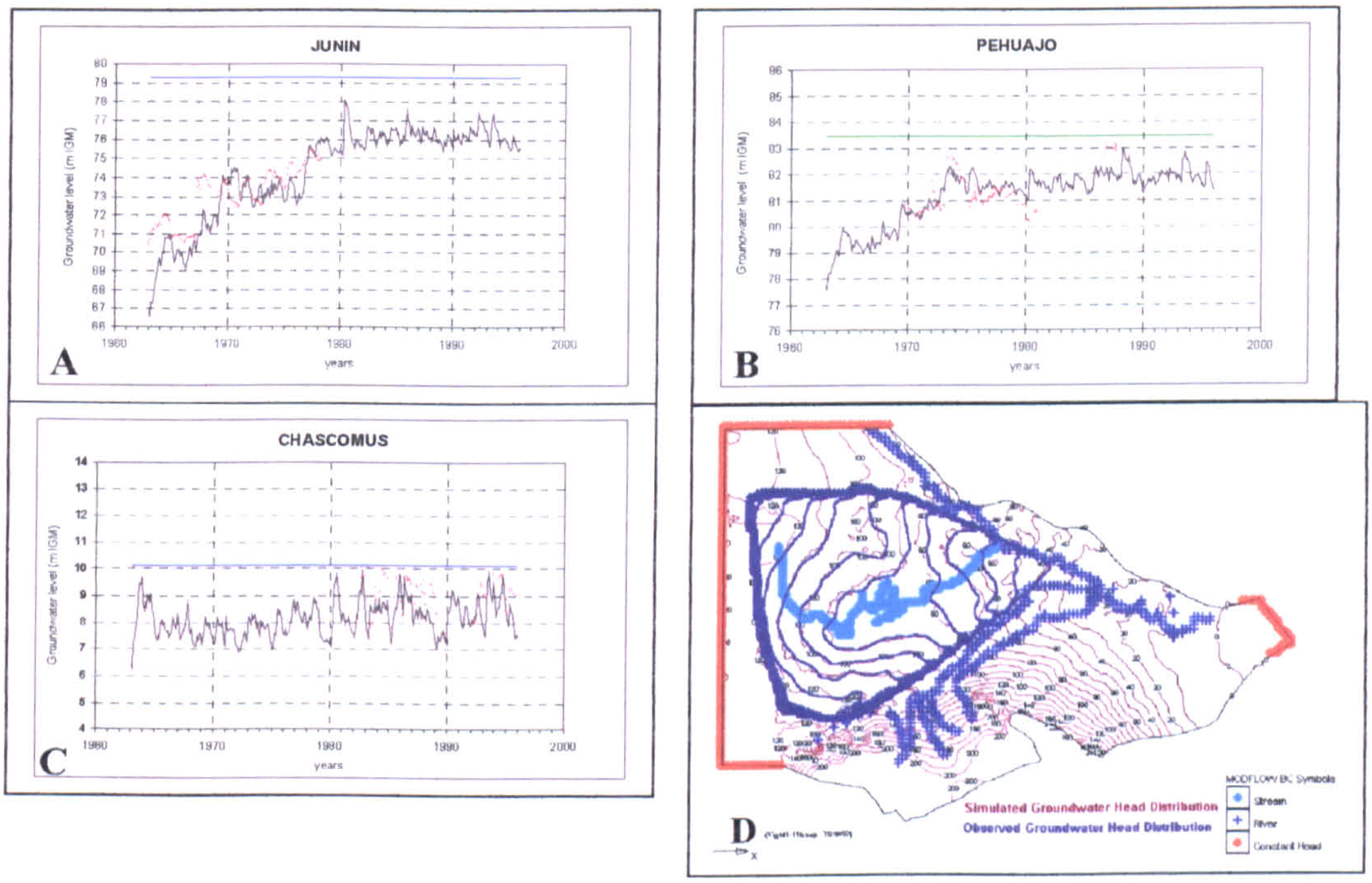


Figure 5.7: A, B and C: Simulated and observed groundwater hydrographs at selected key locations. D: Simulated and observed groundwater head distribution (AyEE, 1990, for which observed borehole data was only available for the Northwest area)

The results obtained from the groundwater balance confirmed the conceptual understanding described in Chapter 3: an important increased in storage has taken place as a consequence of an increase in total recharge over total evapotranspiration: 80% of this increased occurred before the big flood event of 1987; lateral groundwater flows are several orders of magnitude lower than the vertical inflows and outflow; and the exchange of flows with the fluvial system is very low as a result of a predominance of low differential heads between groundwater levels and the levels in the water courses. Table 5.6 summarises the water balance from MODFLOW from a historical (calibration) simulation from 1963 to 1995.

Inflow to active flow system (10^3 Hm^3)	**Outflow from active flow system (10^3 Hm^3)**
Storage (1) = +1081.5 *(+623.6)*	Storage (2) = -1204.5 *(-722.8)*
Recharge = +3674.1 *(+2076.4)*	Recharge = 0.00 *(0.0)*
ET=0.0 *(0.0)*	ET = -3554.8 *(-1981.4)*
Inflow from model boundaries = +7.09 *(+4.56)*	Outflow from model boundaries = -3.28 *(-1.51)*
Inflow from rivers and lakes = +2.55 *(+1.62)*	Outflow from river and lakes= -0.52 *(-0.28)*
Inflow from canal Jaureche = +0.14 *(0.0)*	Outflow from canal Jaureche = -2.06 *(0.0)*
Total inflow = +4765.2 *(+2706.2)*	**Total outflow = -4765.2** *(-2706.2)*

Table 5.6: Overall groundwater balance obtained from the model at the end of a simulation from 1963-1995. In brackets and italics underlined, the results from the period 1963-1985 are presented. Column (1) represents the amount of water that leaves storage to contribute to the flow system, whereas column (2) represents water from the flow system that contributes to storage of the system.

5.2.7 Regional Surface Water Model

Although the RSWM is not directly relevant to the issue of GW-SW interaction within the test area, previous chapters explained the relevance of the fluvial aspects when analysing basin-wide impacts. Therefore, this section presents a brief description of the development of this model.

The objective of the RSWM was to simulate conveyance of water through the network of rivers and canals, providing guidance on the level of impact in downstream catchments of drainage measures proposed in the upper part of the basin, such as in the test area. Also, it was used to investigate the impacts of engineered measures that are directly related to the drainage system, such as: flood embankments, flood alleviation channels, in line/off line storage, and channel improvements.

Hydraulic structures and more than 2000 km of rivers and canals were included in the iSIS model, if they met one or more of the following criteria:

(i) river and canals forming the trunk of the drainage network and are therefore responsible for conveying most of the excess volume of water during a flood event,

(ii) canals or rivers providing a connection (and hence a potential transfer) between different parts of the drainage system,

(iii) hydraulic structures contributing to some kind of regulation in the main drainage system,

(iv) water bodies contributing to storage in the system or those for which a water level is required to feed other studies, such as: flood protection of a nearby town, tourism or fisheries, and

(v) other elements that could form barriers or impedements to flow in the system (causing backwater effects) such as undersized bridges or culverts in the floodplain and roads transverse to floodplain flows.

Figure 5.8 presents a schematic representation of the RSWM

The flow boundary conditions of the model were obtained from the event-based simulations carried out with the rainfall-runoff model, whereas the head boundary conditions were selected to correspond to the discharge of each of the rivers and canals into the sea, and mean sea level was adopted as the normal head boundary condition.

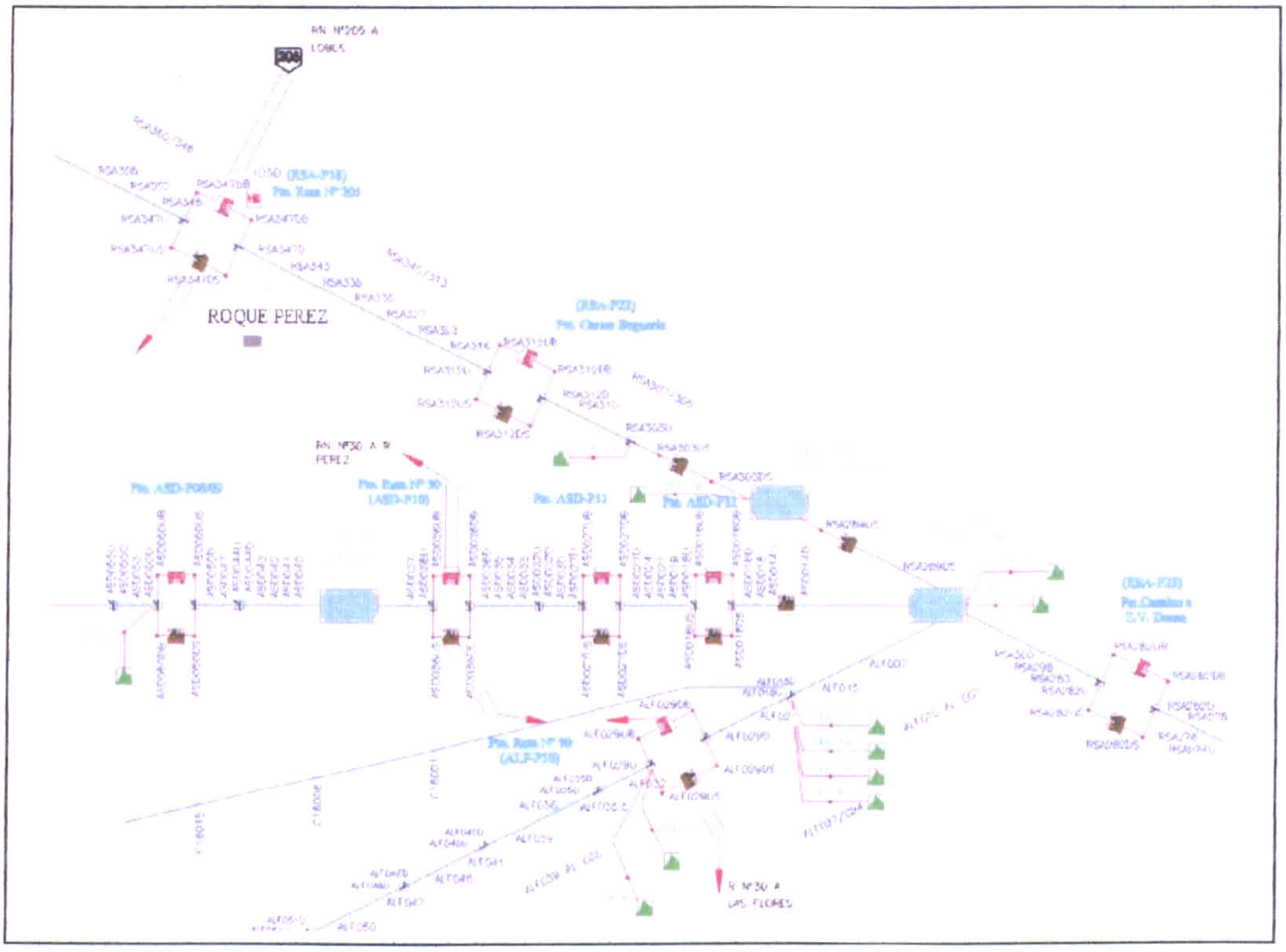


Figure 5.8: Schematic representation of the Regional Surface Water Model

The RSWM was constructed using surveyed channel cross sections with an average spacing of 5km and an average width of 500m to 1000m, which were extended using the Digital Elevation Model to cover the whole extent of inundation during an extreme event. Key features of the system were extracted from cartographic information at scales of 1:50,000 and 1:100,000, and satellite images at a scale of 1:250,000.

A calibration exercise was carried out to prove the ability of the model to reproduce the key mechanisms responsible for causing flooding along the fluvial corridors of the basin (floodplain storage, conveyance, backwater effects, periodical transfers between systems and extreme transfers of water through ephemeral flood routes) and also, its potential to simulate changes in the state variables of the system (flow and level) during the simulation of future scenarios that could be a result of natural changes (like climate variability) and/or engineered interventions. Two extreme events (of a different nature) were selected for the calibration: one occurring during April/May 1980 and the other during November/December 1985. Simulated flow and level hydrographs were compared to observed values sparsely available throughout the system. Also, the predicted flooding pattern was visually compared to that interpreted from satellite images. A satisfactory calibration was achieved by adjusting the roughness coefficient in floodplains and channels, and also, by making modifications in the schematisation to reproduce as accurately as possible the flood paths that took place during an extreme event. An example is the breaching of embankments along flood alleviation channel that intercept old, natural floodplain flow paths.

The outputs of the RSWM were flow and level hydrographs at every node of the system, for the calibration events and for each of the baseline scenarios. The latter involved simulating synthetically-generated flood events for different return periods, ranging from 2years to 100years.

5.2.8 Representation of Groundwater and Surface Water Interaction

As shown in Figure 5.1 no coupling between MODFLOW and iSIS was implemented: In fact, throughout the preceding paragraphs it was highlighted that both models were run for completely different scenarios: the RGWM was used for long-term simulations (33 years with a monthly time step) and the RSWM run on an event basis, with durations that did not exceed one year and with an hourly time step.

Simplified coupling between both processes was adopted as part of the regional modelling strategy. The MODFLOW RIVER package was used to represent the main elements of the drainage network (such as the Rio Salado and the Arroyos Vallimanca and Las Flores), whereas the STREAM package was used to simulate the drainage canals such as the Jauretche-Mercante canal and the El Hinojo-Las Tunas discharge lakes.

Both modules used a similar approach to simulate the transfer of water between the aquifer and the surface features by applying Darcy's equation in the following form:

$$Q_{riv} = CSTR * \left(HRIV - h_{i,j,k}\right)$$

where,

$Qriv$ = flow from a river to an aquifer cell or vice versa (L^3T^{-1}),
$HRIV$ = water level assigned to the reach of the river that coincides with the aquifer cell that it interacts with (L),
$h_{i,j,k}$ = head in the aquifer node underlying the river reach (L), and

CSTR = streambed conductance ($L^{-2}T^{-1}$) defined as:

$$CSTR = \frac{K * L * W}{M}$$

where,

K = hydraulic conductivity of the streambed material (LT^{-1}),
L = length of the river reach (L),
W = width of the river (L), and
M = thickness of the streambed material (L).

The key assumption underlying the functioning of the RIVER module is that the water level for each of the reaches is constant throughout the simulation: The surface water level is not adjusted, with the amount of water entering or leaving a river reach and, therefore, the continuity equation in the surface water system is not satisfied. The STREAM module uses the same equation to calculate the transfer of water between the systems, but mass balance in the surface system is satisfied as the volume emerging from the aquifer is accumulated in the direction of the flow. Despite the fact that an option is available to calculate a water level for each stream reach (based on the flow and the Manning's equation), no flow routing is performed and water is instantaneously propagated in the downstream direction.

5.3 The Regional Flood Probability Maps (FPMs)

A master plan study for catchment management must be supported by analysis of the baseline situation (without project scenario) followed by comparative analysis of the set of measures (structural and non-structural) proposed for each area (with project scenario). FPMs can be used to estimate impacts on affected areas for different return periods for each of the two scenarios; the resulting "benefitted" areas then provide the basis for integrated economic, social and environmental analysis of the proposed measures.

Chapter 4 described the production of FPMs conceptually. This section describes the different scenarios used for model and analysis for which the use of FPMs and modelling results was essential. Initially, a historical FPM was developed based on application of the RGWM model using infiltration and evapotranspiration time series from 1963 to 1995 and a set of starting heads representing groundwater levels prior to 1960 when drier condition prevailed in the region. This map is supported by a set of sparse records and evidence that show that groundwater heads were approximately 10m to 15m below ground level. Figure 5.9 shows the resulting flood probability map for the historical scenario both for the entire basin.

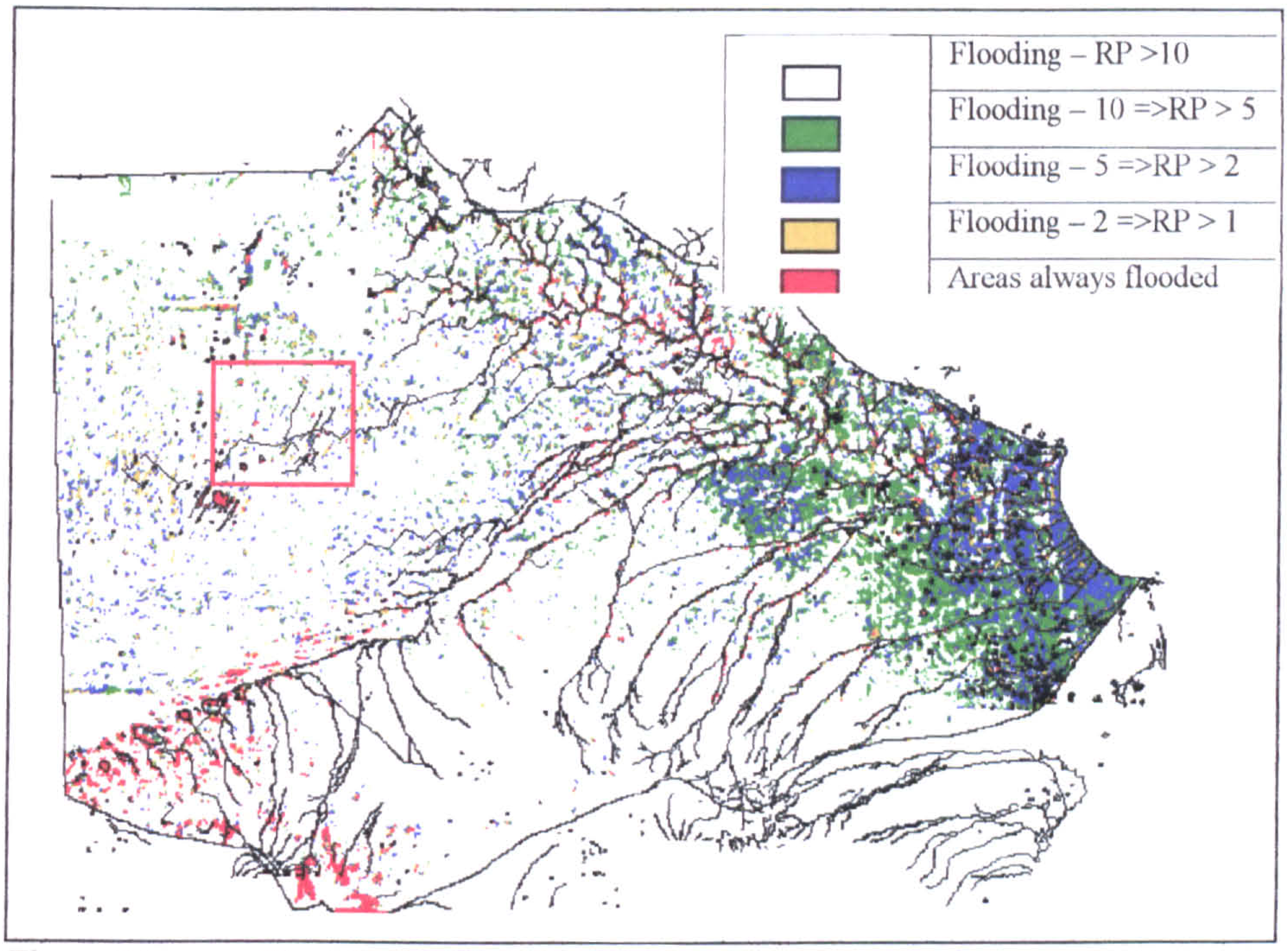


Figure 5.9: Flood Probability Map. Historical Scenario. (RP= return period)

The importance of the historical simulation lies primarily in the need to verify the adequacy of the model to reproduce the dynamics of flood probability in the region, in particular in the test area where the change in flooding pattern was very noticeable with high impact in the agricultural activity.

A second FPM (the baseline map) was constructed using the same hydro meteorological data but with a different set of starting heads. In this case, instead of using as a starting point the conditions prior 1960, groundwater levels obtained at the end of the historical simulation (1995) were used as the initial heads for the baseline simulation. Groundwater heads in the test area show a clear upward trend that started in the 1960's until they reached a new equilibrium in the 1980's that lasts until the end of the simulated period. This indicates a degree of non-stationarity behaviour in groundwater heads that cautions us about the inappropiateness of using the series in any statistical sense. Therefore, a more representative set of initial conditions (in equilibrium with the current climatic situation) is obtained by using groundwater levels extracted for any year after the rising trend began. The period prior to 1990 was not chosen as it was considered that the system could still be affected by the big flood events that took place in 1986 and 1987. Similar thinking indicated that 1995 would be a suitable year, following the occurrence of another flood event in 1993. Figure 5.10 shows the resulting flood probability map for the baseline scenario for the entire basin.

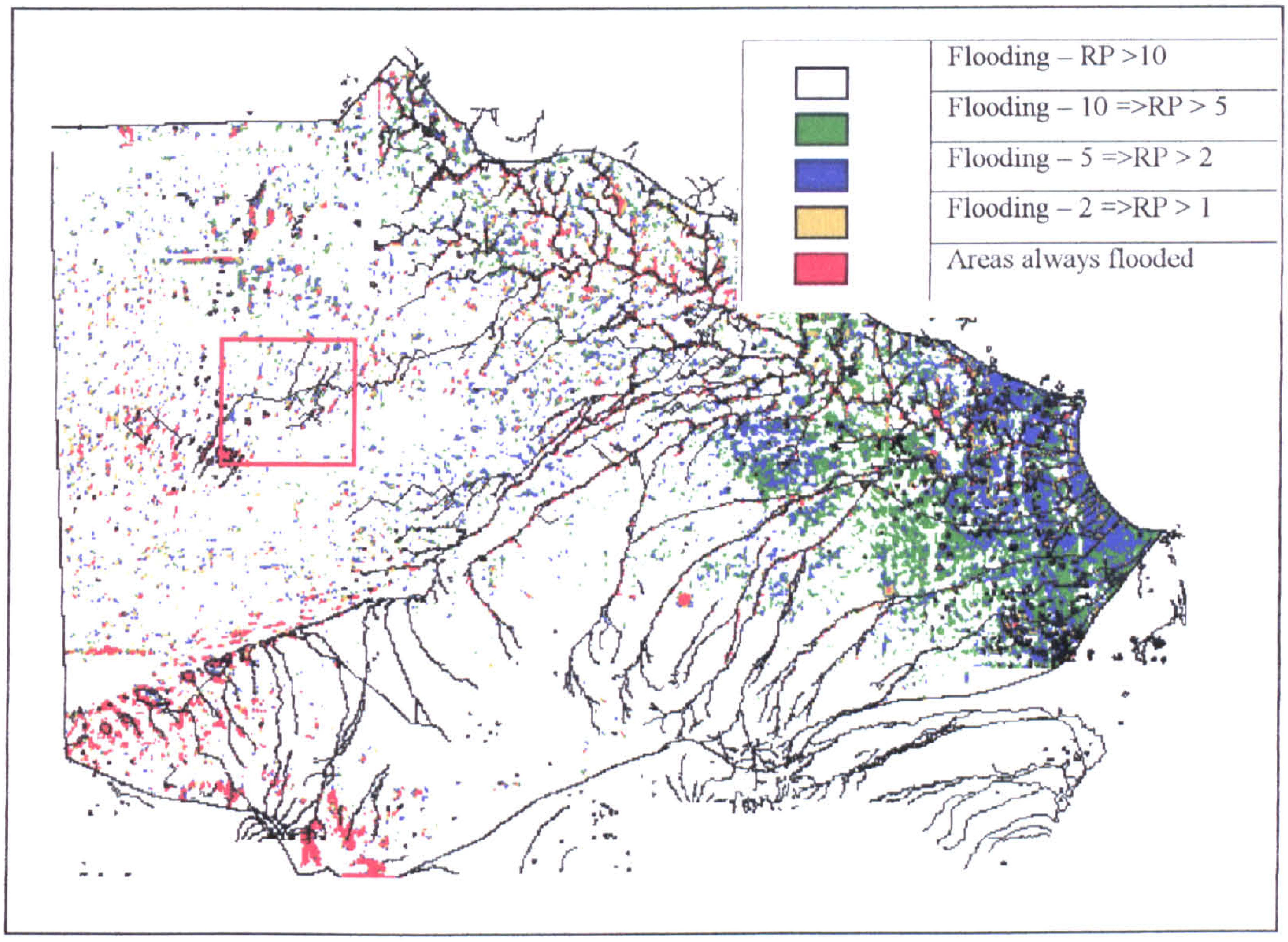


Figure 5.10: Flood Probability Map. Baseline Scenario. (RP= return period)

Finally, a third FPM was developed to map the residual affected after implementation of the proposed drainage measures to relieve flooding and waterlogging in the Northwest area. Implementation of a new drainage system in this region would represent one of the most challenging aspects of the engineering measures to be put in place and, therefore, a careful design would be required. Besides the analysis of its future likely impact on the natural environment of the region, two interrelated issues need to be addressed: the required capacity of the open surface drains (*drainage rate*) and the return period event that they will have to protect against (*levels of service*).

Drainage rate can be defined as the average flow of water to be used to size a drainage system designed to evacuate the excess runoff generated for an event of a specified return period, and it is usually expressed in millimetres per month (mm/month).

Level of service implies that something is developed fit-for-use or "service" under particular conditions or "level". In the case of the test area, the use of service is defined as "fit for a particular agricultural land use" and the condition or level is "at the frequency or return period that would cause flooding or waterlogging".

For a conventional flood control project, if the conveyance capacity of the scheme is exceeded and a property floods every 10-years, then the level of service is 10 years. In the case of the test area, with the predominance of agricultural enterprises, the relationship is not so straightforward. The level of service has to be defined not only by the level of prevention that the new drainage infrastructure provides but also in terms of how well the new system will enable a particular form of land use (not any land use) to be carried out. Expressed from a different angle, in a conventional flood control project, one can interrogate the system by asking whether a piece of land floods or does not flood. In the case of the evaluation of rural projects (and benefits), the question is different: does the new drainage system enable or does it not enable a change (or a positive modification) in the land use practised under the current circumstances.

Within the IMP studies, the RGWM was used to generate the *with-project* FPM. The time series of monthly infiltration rates used for the baseline scenario was modified, prior to its use in a with-project simulation. This assumes that:

(i) surface runoff simulated by the rainfall-runoff model was assumed to be first conveyed by the new drainage system making use of its maximum capacity,

(ii) residual excess runoff (not conveyed by the drainage system) is retained on the surface and available for evaporation and for further conveyance through the drainage system once its capacity is released,

(iii) if at any time, the drainage capacity exceeds the excess runoff (including any runoff stored from previous time steps), then it is assumed that the drains are available to take water out of the aquifer. However, for this operation, it was assumed that only 50% of the full capacity of the drains would be available for draining off the aquifer on the basis of normal (seasonal) groundwater fluctuations (with a maximum of 0.5m to 1m below ground level) which will provide the driving head for flow into the drains. When there is a flood event, ground water levels will be close or at above ground level, a higher driving head will be available and the drains would operate at their design maximum rate.

The cost-benefit analysis demonstrated that 10 years was the optimum standard of protection against groundwater-induced flooding in the North West area. Figure 5.11 presents the resulting map showing the areas that would benefit from the implementation of the flood defence scheme through construction of the proposed drainage system.

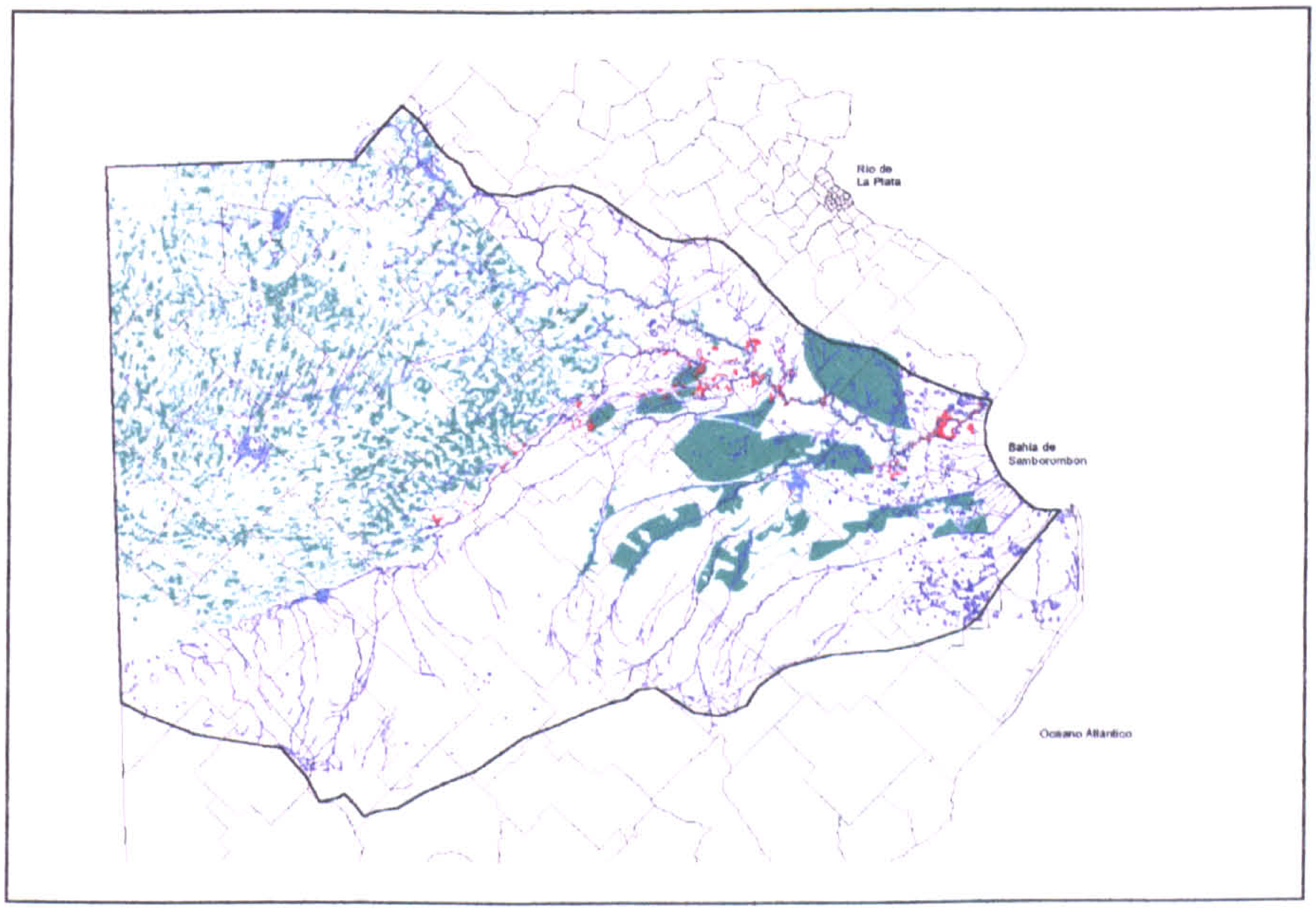


Figure 5.11: Total area that would benefit from the implementation of the structural measures proposed in the IMP.

5.4 MODFLOW Approach to Deal with SW-GW Interaction as Part of the Calculation of FPMs

This section focuses on analysis of the suitability of the approach adopted to develop the RGWM with MODFLOW to derive FPMs for the test area. Figure 5.12 presents the location of two sections of analysis, which run along an interdunal depression and orthogonally across a series of dunes respectively.

The analysis of the suitability of MODFLOW was focused in the results obtained for 1987/1988 as it is the period where the largest flood event that affected the test area took place.

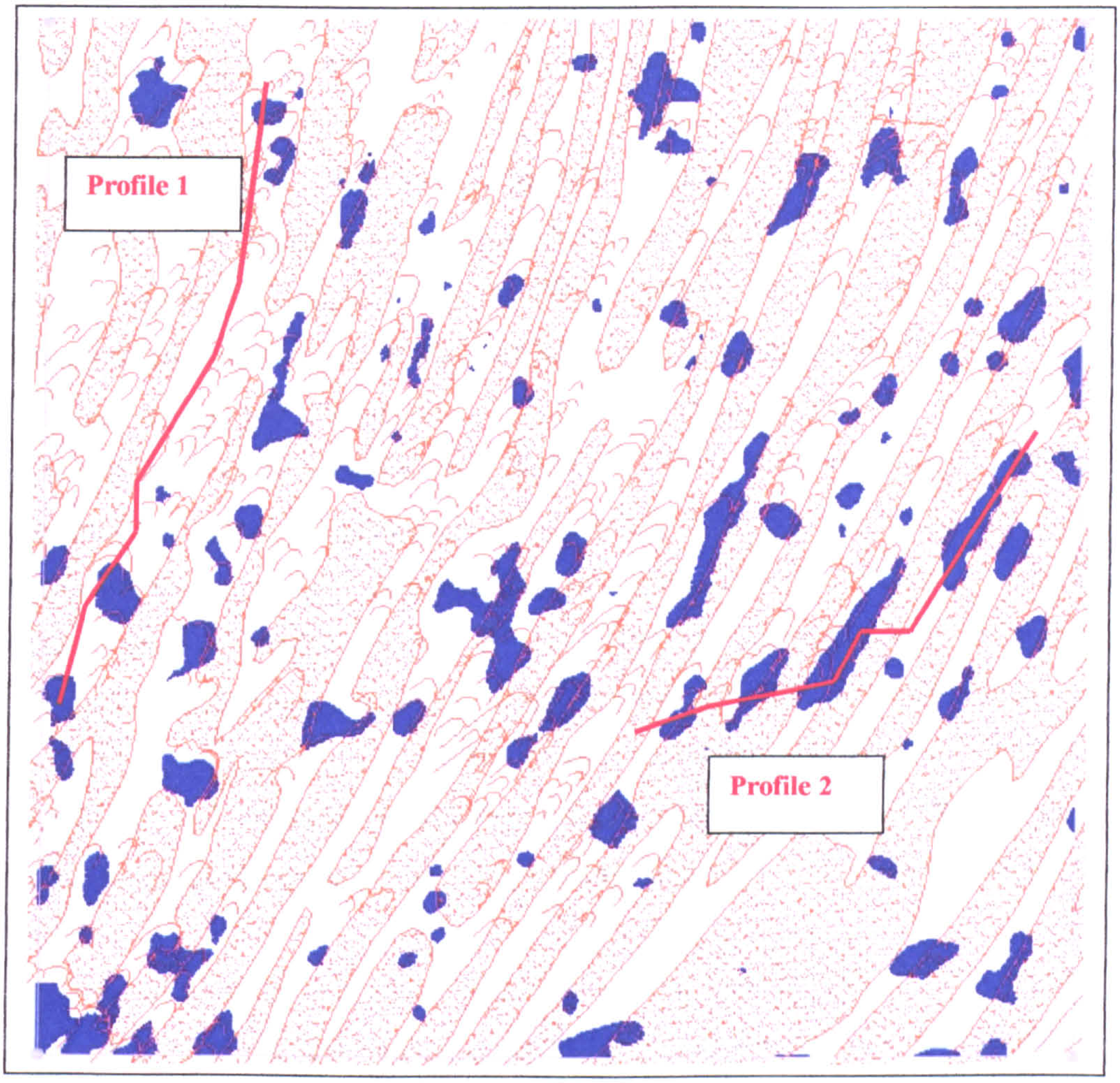


Figure 5.12: Location of the two sections of analysis.

Figure 5.13 presents a long section along an interdunal depression of the test area, showing the 5000m-ground surface (used by the MODFLOW evaporation package to calculate evaporation as a function of water table) together with the 5000m- groundwater heads obtained from the RGWM for the wettest month in that period. Figure 5.14 presents the same series of data, but for a section orthogonally across the dune field. Two things emerge from the figure: First the groundwater heads mimic very closely the profile of the surface used by MODFLOW to calculate evapotranspiration. A sensitivity analysis was carried out decreasing the extinction depth from 3m to 1.5m, showing an identical pattern but with groundwater heads closer to the surface. This is expected as a reduction of extinction depth decreases the amplitude of seasonal variation of groundwater heads, reducing the total amount of evapotranspiration extracted from the system. Second, groundwater heads do not exceed the ground surface, even for the wettest month of the simulation period, what implies that the RGWM *per se* fails to identify groundwater induced flooding. However, some flooding is detected when combining the results of the model with a 500m resolution DEM (see dashed line in Figure 5.13 and 5.14). This leads to another two issues. One is that the identification of flooding is clearly independent of the calculation of the groundwater profile and second that the number of areas identified as being flooded will depend on the relative height difference between crests and depressions in the dune field and the actual spatial distribution of micro-relief features compared to the resolution adopted for the groundwater model. Figures 5.13 and 5.14 also show that the approach with MODFLOW can equally underestimate or overestimate groundwater-induced flooded areas as depths of water on the surface are not reproduced correctly. Not reproducing depths of water in the surface does not necessarily imply a problem in the generation of a FPM if this is just concerned with the detection of a flood/no flood situation; however what is of concern is matching the right locations where flooding occurs. The approach described so far failed to do so.

The resolution of the test area model was incresed from 5000m to 500m to test the sensitivity of the approach to a change in the resolution of the groundwater profiles. In this case the surface used to calculate evaporation in MODFLOW coincides with the resolution of the DEM. The stress in the model was maintained constant and a monthly infiltration time series was used. Figure 5.15 shows a groundwater profile along an interdunal depression, indicating that heads very closely match the features of the ground surface, and that the identification of GW-induced surface flooding could be more accurate. However, the limitation of the approach in calculating correct depths of water at the surface still remains as it is an inherent limitation of MODFLOW.

Another exercise was investigated by simulating a daily time series of infiltration to test the sensitivity of the approach to the temporal resolution of the stress. Figure 5.16 presents a sequence of groundwater profiles along an interdunal depression in the test area. The first thing to be noted is how fast the groundwater heads accommodate to the ground surface, as can be noted by examining the difference between the starting heads (obtained from the RGWM) and the rest of the profiles, which show again the tight control imposed by the evaporation in the system. However, the most noticeable point is that, in this case, the maximum profile exceeds over the entire ground surface profile, totally overestimating the number of locations where GW-induced surface flooding occurs.

A third exercise was carried out to analyse the ability of this approach to reproduce the dynamics of surface flooding. Available interpretation of surface flooding from satellite imagery was used to analyse the results of the model. Figure 5.17 presents the interpretation of flooding form the satellite imagery, while Figures 5.18 and 5.19 present a mosaic of pictures with the results from the various simulations carried out for the test area. A comparison of model results with the surface flooding captured by the satellite images reflects the clear inability of this approach with MODFLOW to represent the dynamics of water at the surface. Increasing the resolution of the model allows identification of more areas subject to flooding (right image in Figure 5.19) but the number of times (months) for which flooding is detected decreases. Using a daily time series of infiltration would have not made any improvement as the results show (consistently with the long profile shown in Figure 5.16) that the entire test area would be under surface flooding.

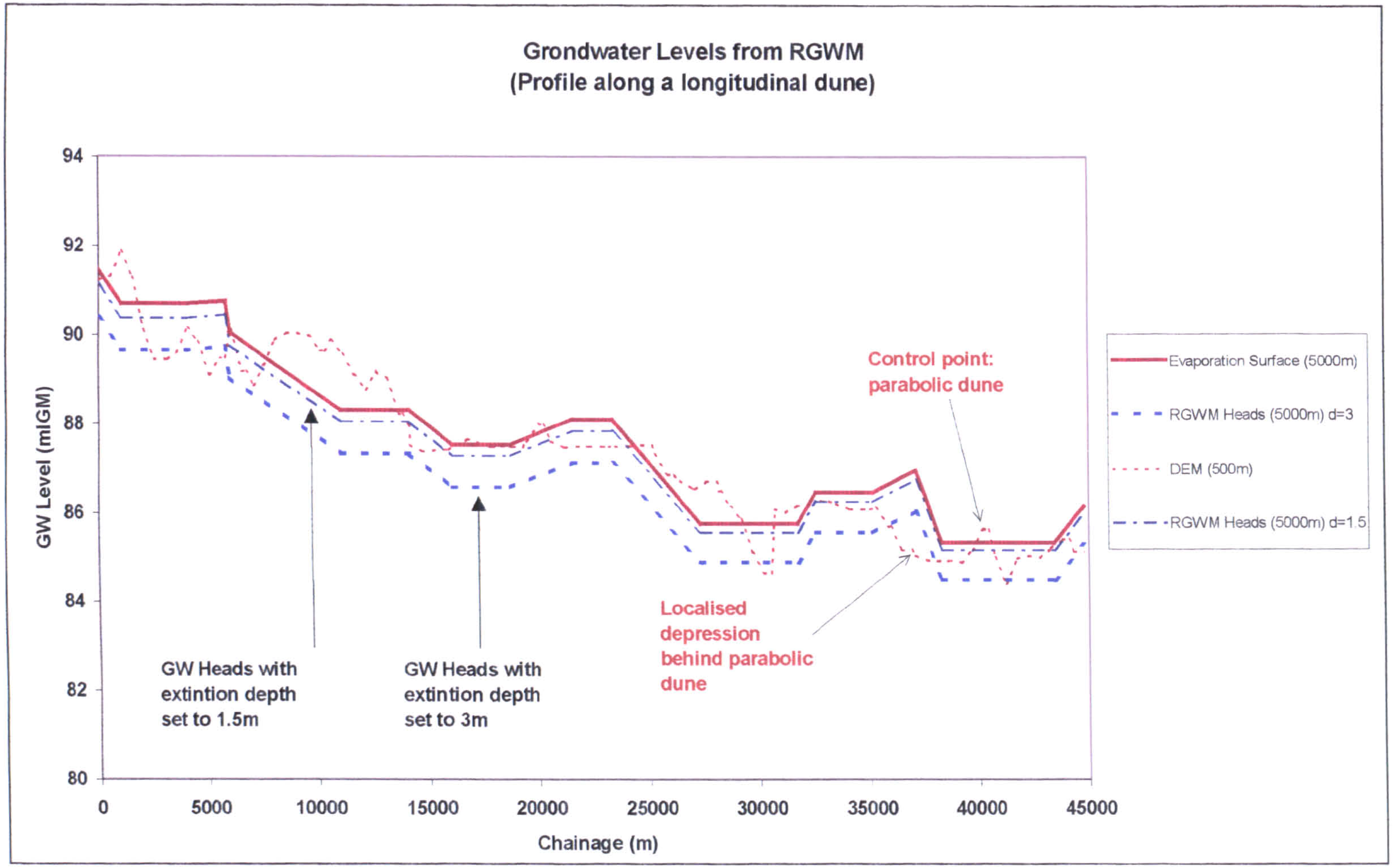


Figure 5.13: Groundwater levels along an interdunal depression of the test area

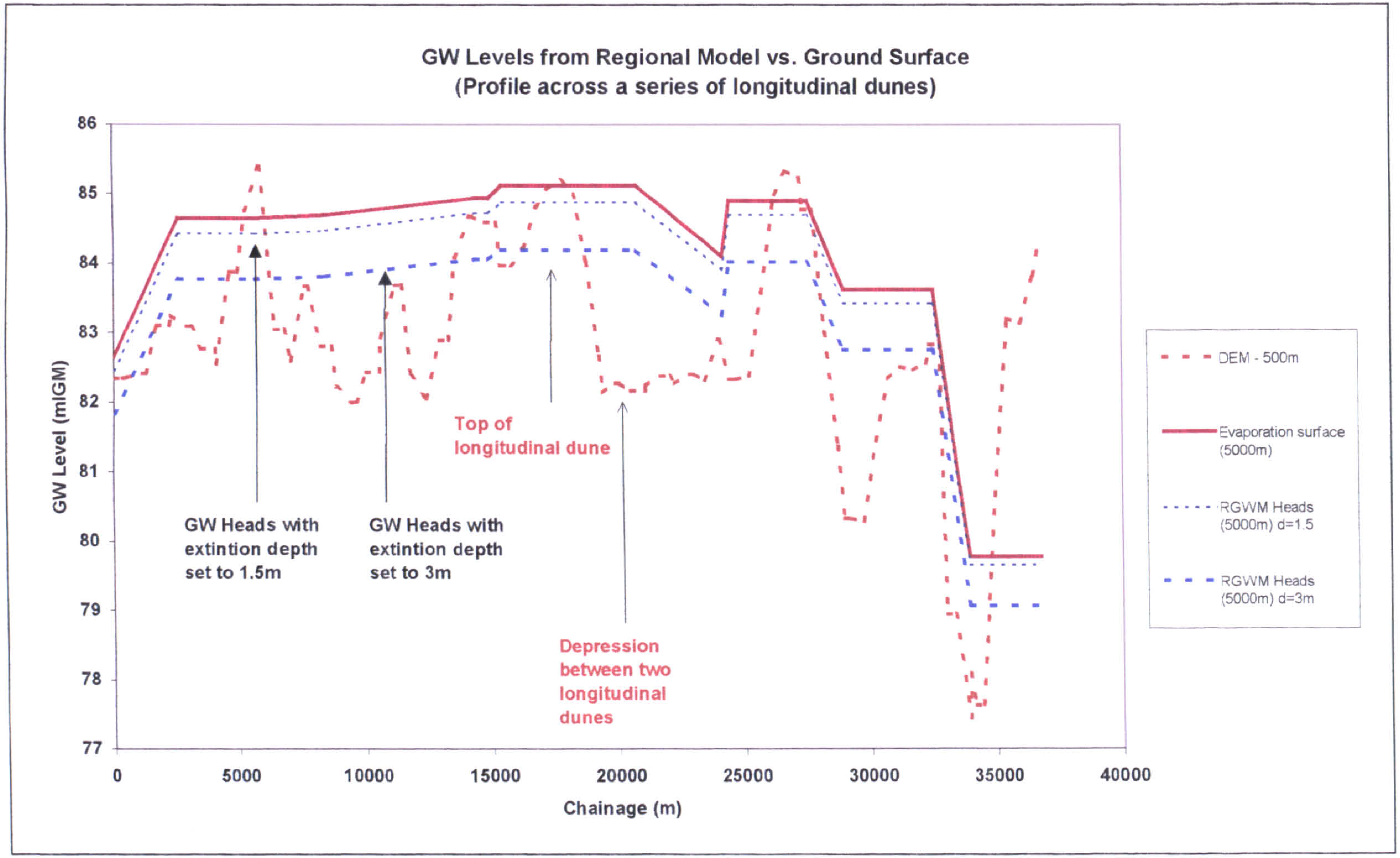


Figure 5.14: Groundwater levels along a cross section of the dune field in the test area

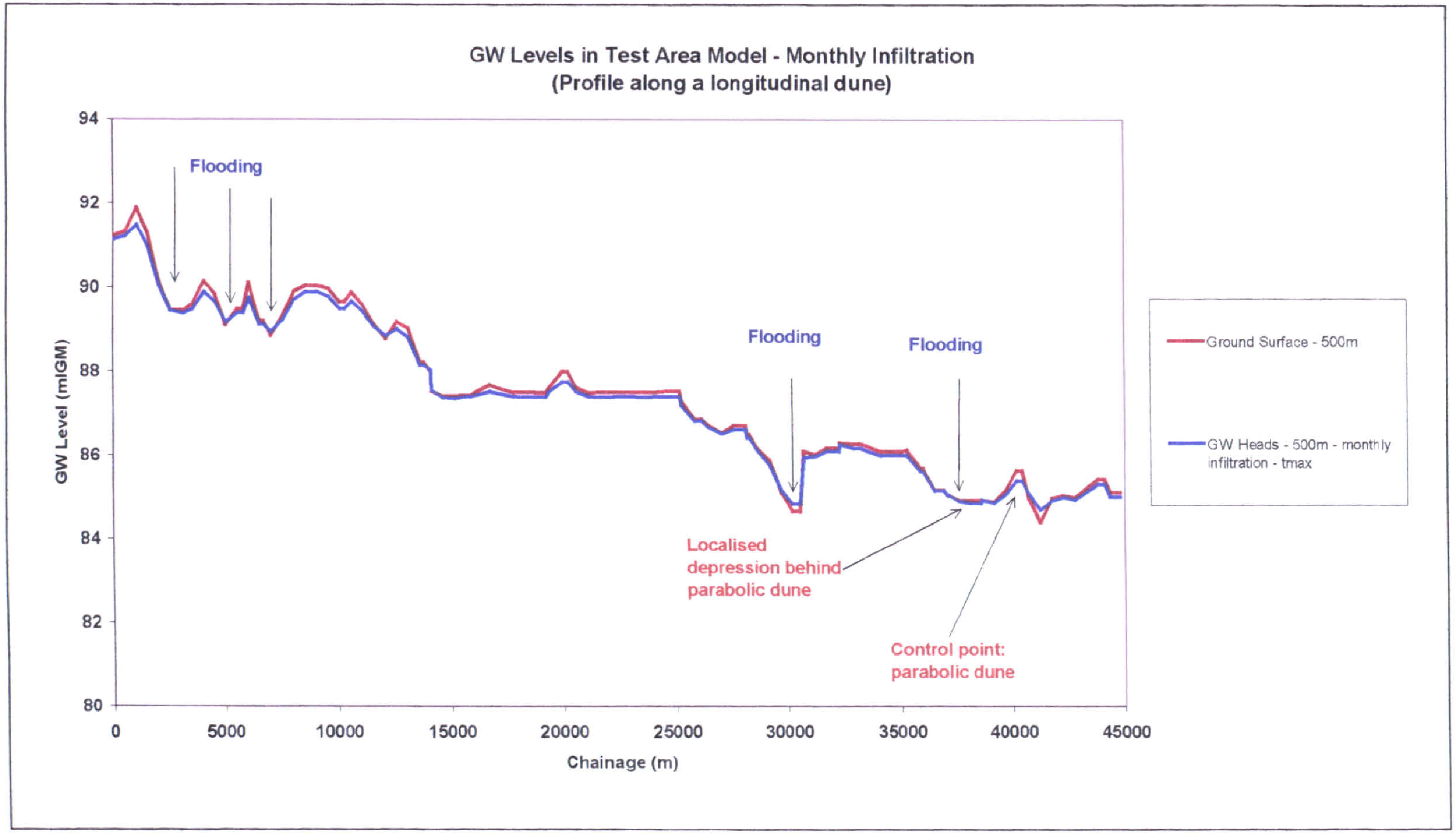


Figure 5.15: Groundwater levels along an interdunal depression in the test area. Test Area Model. Monthly Infiltration values.

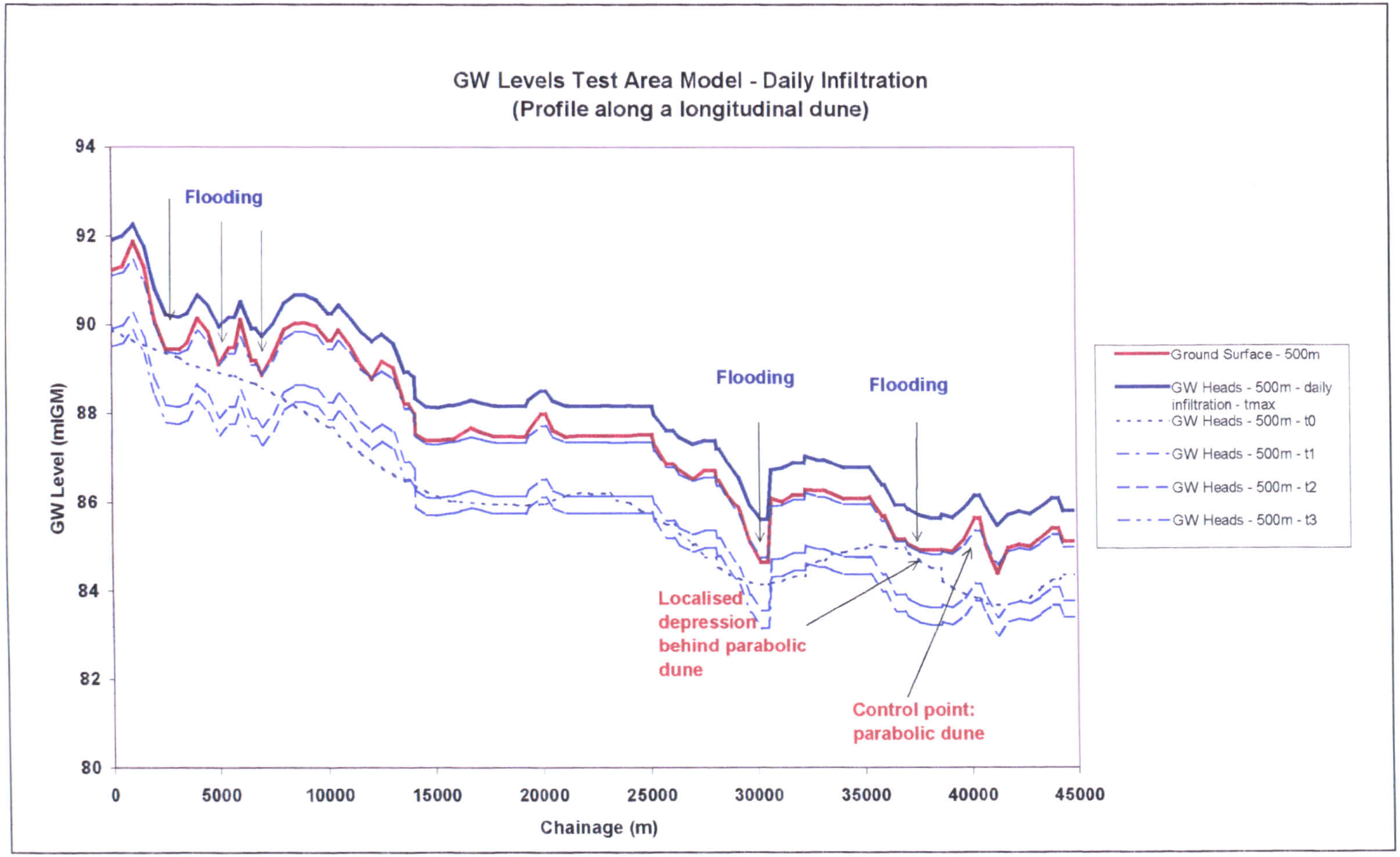
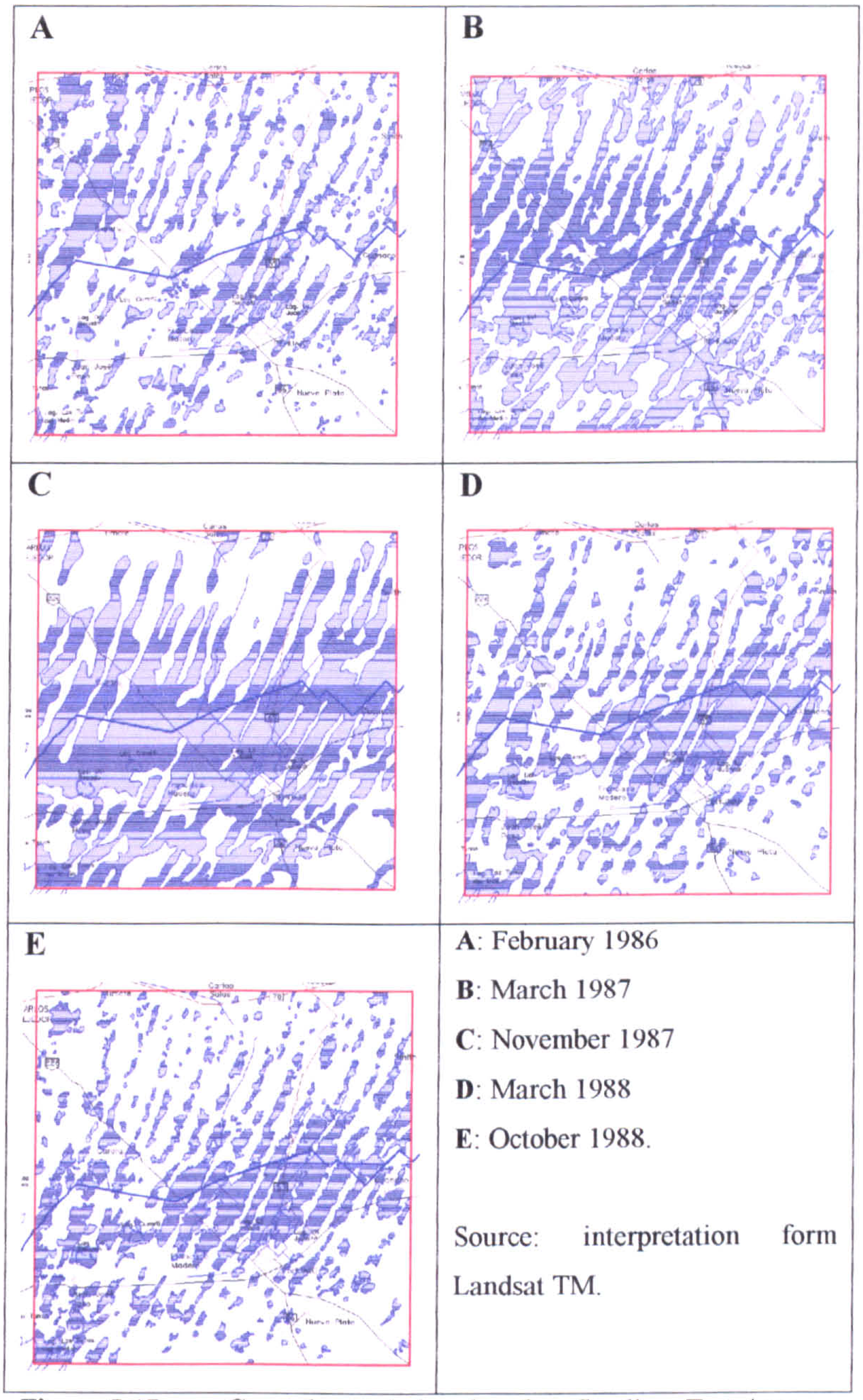


Figure 5.16: Groundwater levels along an interdunal depression in the tet area. Test Area Model. Daily Infiltration values



A: February 1986

B: March 1987

C: November 1987

D: March 1988

E: October 1988.

Source: interpretation form Landsat TM.

Figure 5.17: Groundwater induced surface flooding. Test Area.

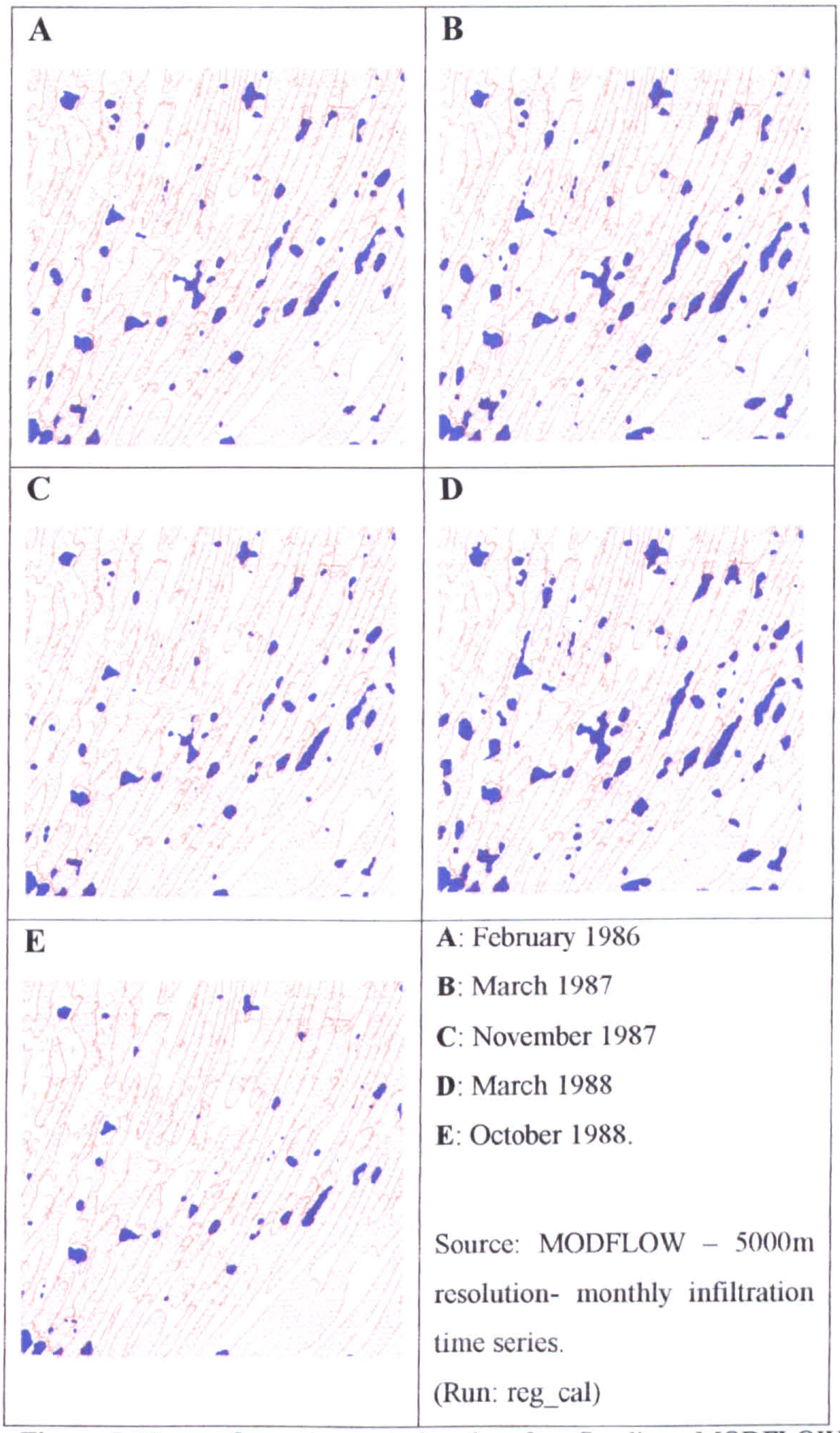


Figure 5.18: Groundwater induced surface flooding. MODFLOW only.

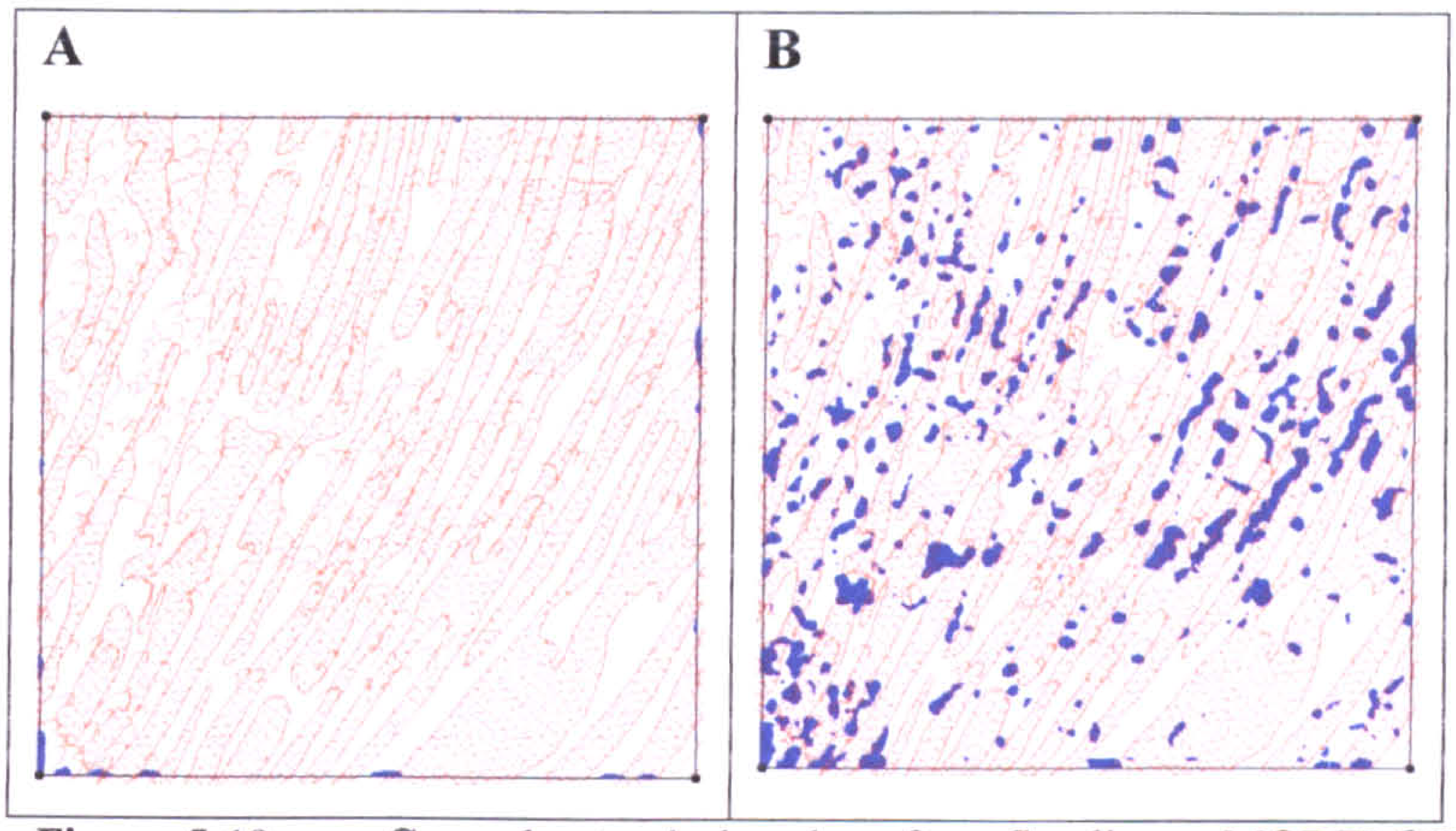


Figure 5.19: Groundwater induced surface flooding. MODFLOW only. A: November 1987. B: March 1988. Source: MODFLOW – 500m resolution - monthly infiltration time series. (Run: run11)

In conclusion, using MODFLOW only to generate FPMs is not a robust approach and can only yield an approximate identification of surface flooding, failing to estimate the correct depths of water on the surface. In fact, its use for mapping the frequency of surface flooding is tightly linked to a set of factors concerning the schematisation of the model. Forcing the resolution of the groundwater model to match the resolution of the micro-relief features helps to identify more precisely the location of flooded areas. However, the fact that results are also subject to the temporal resolution of the stress input into the model (monthly or daily), generates a significant weakness in this approach.

The groundwater heads are strongly influenced by the vertical components of the water balance and, primarily, by the evapotranspiration from the saturated zone and the position of the ground surface. The fact that the horizontal flow is negligible prevents the model having a groundwater profile that is less sensitive to changes in the input stresses and less controlled by the position of the ground surface, as was seen when changing from monthly to daily infiltration.

It must be concluded that use of this approach to estimate which areas would benefit from inclusion of drains will be subject to the same limitations and considerations explained above. Adopting a simplified approach to estimate the effect of drains, i.e. by modifying the time series of infiltration, is the only viable method as it would be incorrect to include the canals explicitly in the model, due to the impossibility of MODFLOW to calculate the correct head of water at the surface to drive water into the drains.

- CHAPTER 6 -

THE DEVELOPMENT OF A COUPLED GROUNDWATER AND SURFACE WATER MODEL: iSISMOD

6.1 Introduction

Chapter 5 described application of MODFLOW as part of the strategy adopted to support the IMP studies for the Salado basin, arriving at the conclusion that this approach had severe limitations in reproducing the GW-SW interaction that is largely responsible for flooding mechanisms that dominate the test area. This led to the conclusion that a fully coupled surface water-groundwater model would be required to overcome those limitations. Prior to the analysis of this approach for the generation of FPMs, this chapter describes the development of iSISMOD, a mathematical model to simulate the interaction between surface and groundwater systems.

In general terms, the coupling of GW-SW processes is important in a number of situations that are implicit when dealing with catchment management planning issues. Figures 6.1A to F show examples of the potential applications of a fully coupled model for surface water and groundwater interaction.

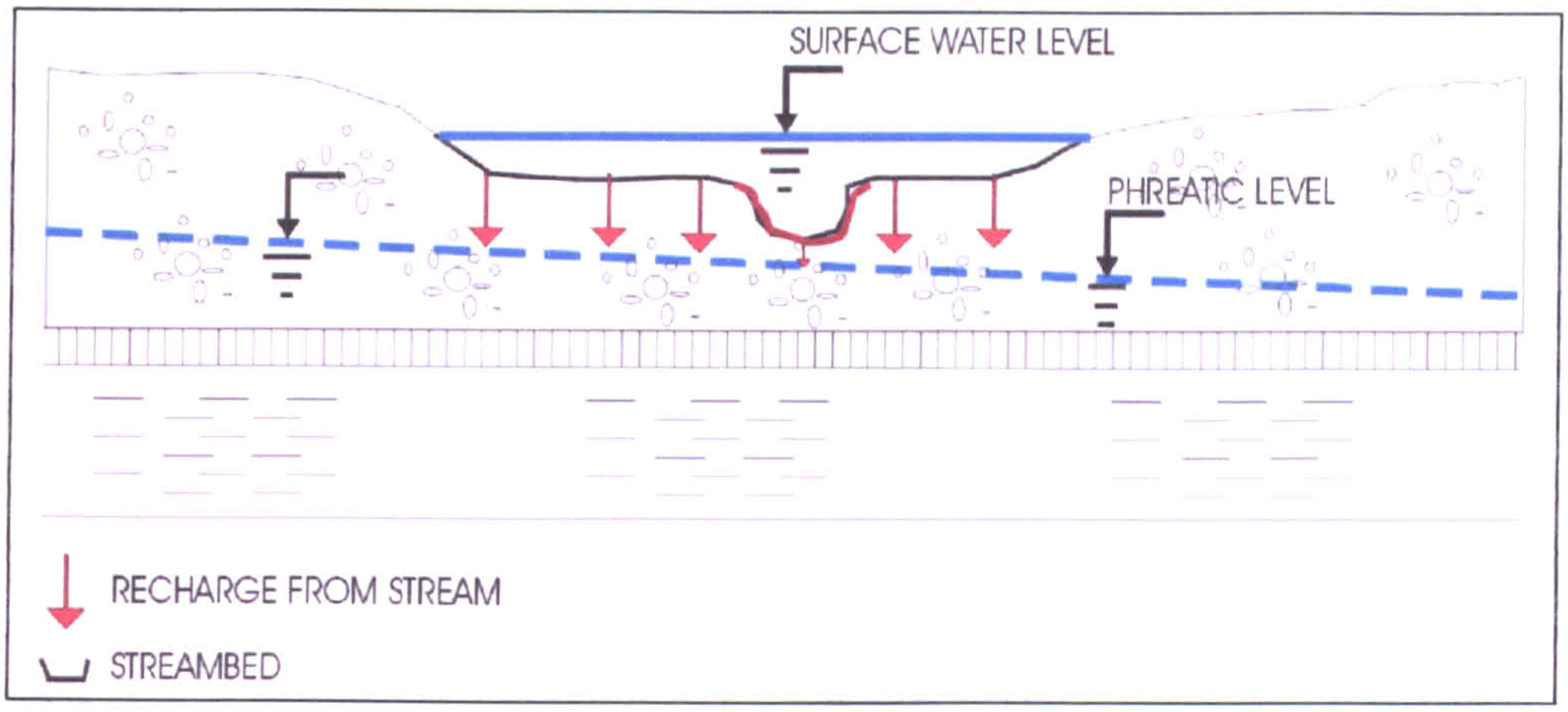


Figure 6.1: **A**. A coupled GW-SW model could be used to estimate recharge from leaky streams to an aquifer. Note variation of streambed thickness between the main channel and the floodplain.

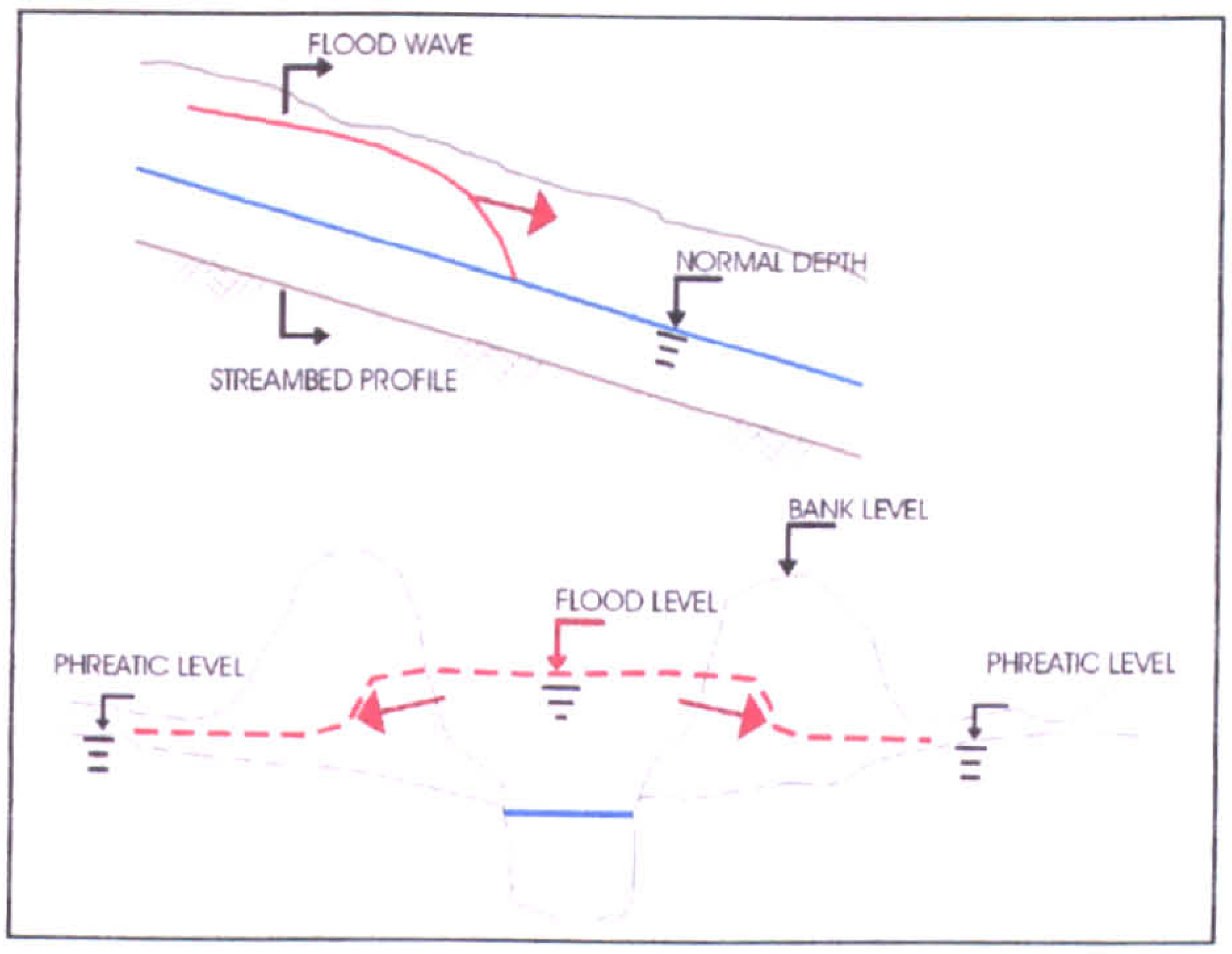


Figure 6.1: **B**. A coupled GW-SW model could be used to estimate bank storage attenuation effects when a flood wave passes along a stream.

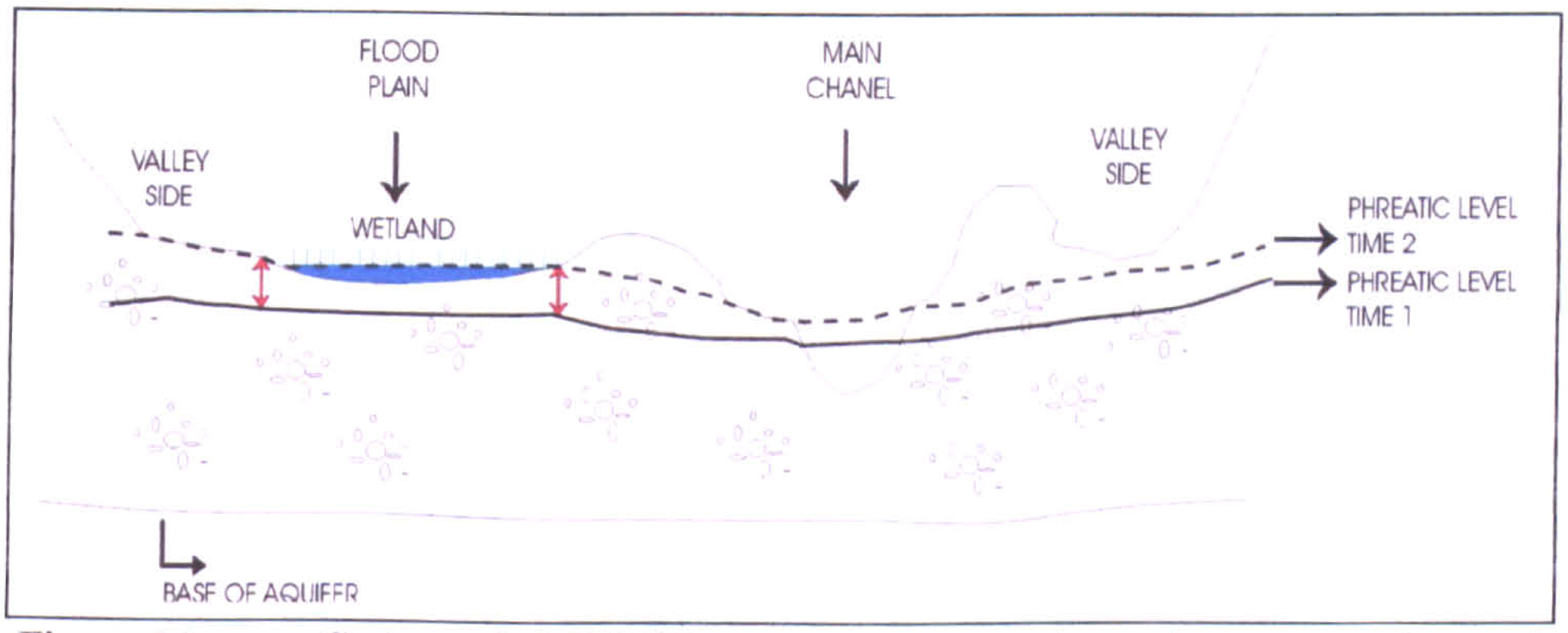


Figure 6.1: **C**. A coupled GW-SW model could be used to estimate seasonal water level fluctuations in the floodplain of a river, allowing the evaluation of the effects on wetland hydrology.

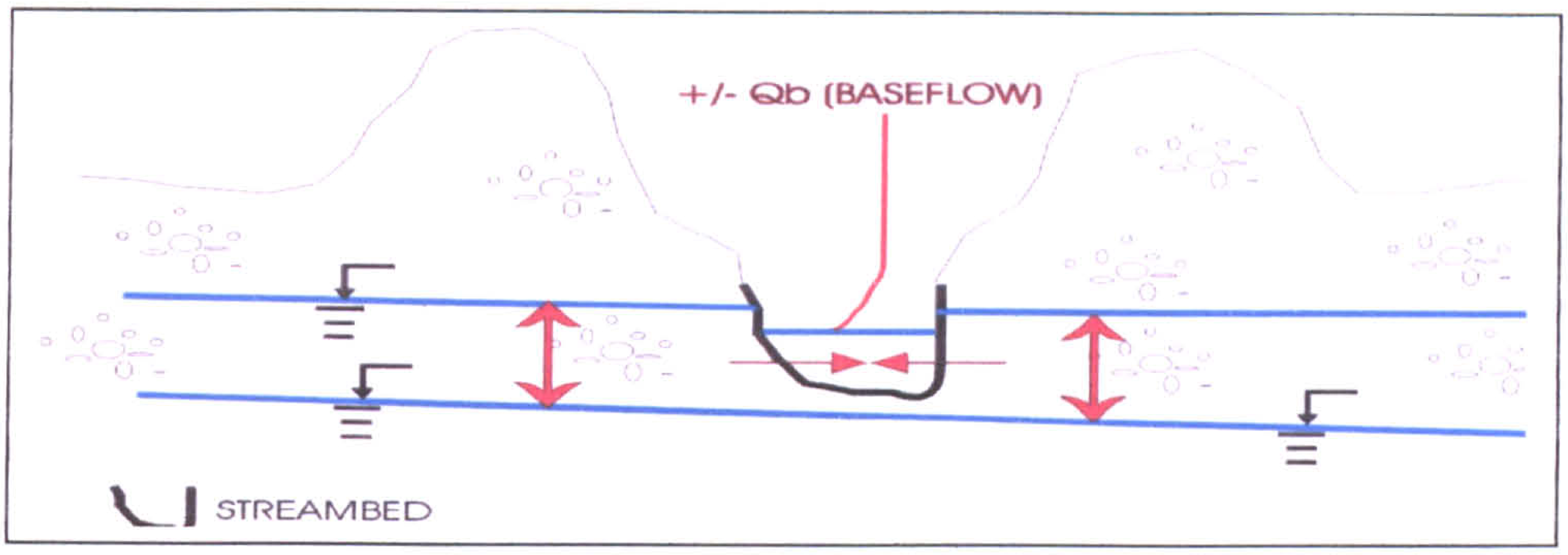


Figure 6.1: **D.** A coupled GW-SW model could be used to estimate the contribution of an aquifer to the baseflow of rivers.

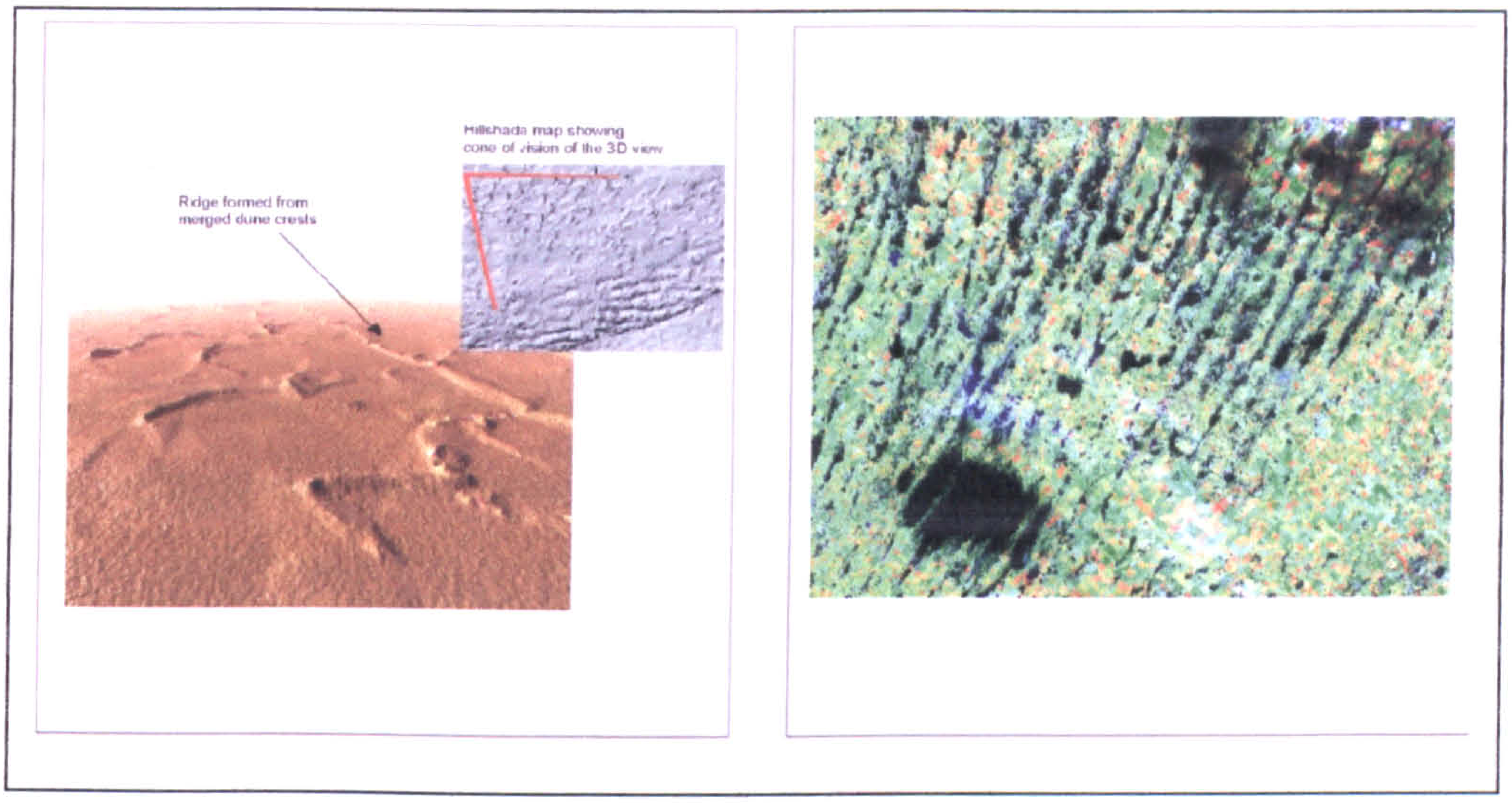


Figure 6.1: **E.** A coupled GW-SW model could be used to predict flooding and waterlogging situations caused by groundwater emerging at the ground surface and so forming variably contributing areas.

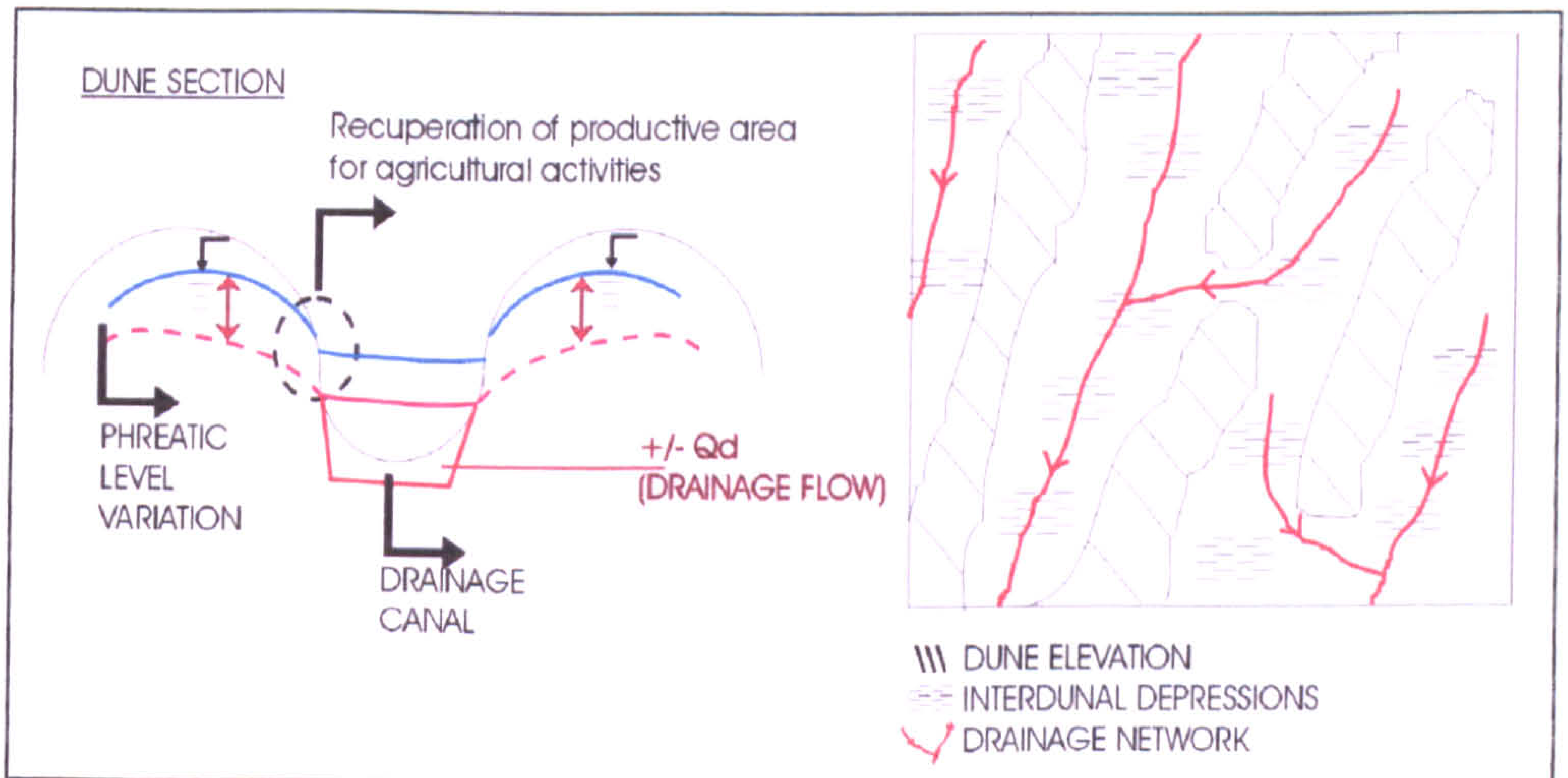


Figure 6.1: F. A coupled GW-SW model could be used to study the management of drainage systems in which the coupling between surface and groundwater processes is a key factor.

6.2 Selection of tools for coupling

Chapter 3 explained the flooding mechanisms that operate in the NW region of the Río Salado basin, and which consist of large saturation return flows that cause extensive, groundwater-induced, surface flooding situations. The roles of various geomorphic features were also explained, as they influence the dynamics (storage and conveyance) of surface water.

The physical processes embedded within the flooding mechanisms are generally three-dimensional in nature and the GW-SW interaction described herein is no exception. Any simulation that seeks to represent the complexity of the processes should take into account the existence of horizontal and vertical fluxes in both the groundwater and the surface water system. However, it is important to acknowledge that all flooding mechanisms also have a dominant process that can be represented in either two or one dimensions with a level of accuracy that is acceptable if the purpose of modelling is to support catchment planning. Table 6.1 lists the individual processes that should be represented within an integrated representation of groundwater-induced surface flooding, analysing the dimensional aspect of the dominant physical mechanism and the approach that could be adopted in modelling terms. This exercise served the purpose of supporting the individual tools selected to develop the new, coupled model that was required to investigate the key issues identified in the thesis.

Process element	Key dimension of process component	Recommended modelling approach
Groundwater flow	3D – Although lateral groundwater flow is small compared to the vertical movement, both are important at a sub-regional scale in order to represent vertical fluxes and horizontal flow towards sub-regional depressions.	3D groundwater modelling using a layered system to represent vertical fluxes.
Exfiltration (return flow)	3D – the appearance of water in the surface can occur from a rise of the phreatic levels (vertical component) or through lateral flow from dune sides to adjacent low lying depressions.	3D – by simulating leakage from the aquifer through the bottom and the sides of each surface water body.
Ponding of exfiltrated water	3D – This requires that the surface area and depth of water are correctly represented.	3D – by including in the representation the depth-area relationship of surface water bodies.
Transfer of water between low areas	3D – The two dimensional aspect is needed to represent the movement of water along a longitudinal depression and also the connection between parallel longitudinal depressions. The third dimension is associated to the simulation of flow over the parabolic dunes embedded in the longitudinal dunes.	A 2D approach is required to simulate water movement through the pattern of longitudinal dunes. A 1D approach is adequate to simulate flow over parabolic dunes as this can be associated as free and/or drowned weir flow.
Saturation overland flow and seasonal expansion and contraction of open surface water bodies	2D – As the exfiltrated water (saturation return flow) appears on the surface, it is required that the areal extent of the saturated area is represented, so that the correct amount of runoff from rainfall falling on these areas is predicted	The modelling must account for the representation of areal growth by using a stage- area relationship as described before. Also it is required to take into account the direct conversion of rainfall into runoff in this area.

Table 6.1: Dimensional aspects of GW-SW interaction. Conceptual issues.

The descriptions in the table above lead to the conclusion that the coupled model requires a 3D groundwater model and a surface water model that is either 2D or is able ro make adequate provision for the simulation of 2D aspects of surface water extent and movement.

MODFLOW complies with all the requirments to perform a 3D simulation of a groundwater system (see also Chapter 2), while iSIS Flow, a 1D surface water model, can also represent adequately all of the 2D phenomena identified in Table 6.1. The way that MODFLOW and iSIS could fulfil the modelling requirements outline above is more fully described in Table 6.2.

Process element	How can iSIS and MODFLOW deal with the modelling requirements
Groundwater flow	MODFLOW solves the 3D continuity and Darcy flow equation of groundwater movement in porous media.
Exfiltration (saturation return flow)	Exfiltration is simulated by including leakage between single or multiple MODFLOW cells and surface water units in iSIS (river or reservoirs units)
Ponding of exfiltrated water	iSIS simulates storage in ponded areas by using the reservoir units that explicitly include a stage-area relationship.
Transfer of water between low areas	Spill units in iSIS (based on a weir equation) can be used to simulate the transfer between adjacent low areas.
Saturation overland flow and seasonal expansion and contraction of open surface water bodies	Reservoir units in iSIS can also represent the dynamics of saturated areas. Chapter 7 explains how iSISMOD deals with the calculation of runoff contribution from rainfall impacting on saturated areas.

Table 6.2: Dimensional aspects of GW-SW interaction. iSISMOD approach.

While the arguments put forward in Tables 6.1 and 6.2 suggest that iSIS Flow seems to be an adequate tool to deal with the modelling requirements, coupling MODFLOW to a 2D surface water model could also have been a valid option.

The use of a 2D model based on the full solution of the 2D shallow water flow equations would have eliminated the need for the coupled model to work over large areas on a iterative basis. For example, Lisflood (Bates and De Roo, 2000), a simple raster-based model for floodplain inundation, is worthy of consideration for providing a more efficient representation of the surface water component for the coupled model. The strength of Lisflood lies in the simplicity of the 2D routing of overland flow, which could make it suitable for dealing with large scales, and the possibility of reducing the effort required in schematisation, as a single layer comprising the entire terrain could be modelled in Lisflood. This program can determine overland flow routes automatically, based on a raster DEM that covers the entire study area. However, Lisflood solves the overland flow routing using a kinematic approach that neglects backwater effects. This could compromise the representation of the flooding process and its relationship with the parabolic dunes placed along the interdunal depressions. Futhermore, even assuming that Lisflood could be used at the diagnosis stage, it would be less appropriate at a project phase as it would not provide all the elements required to analyse the hydraulics of drainage measures required to mitigate groundwater-induced surface flooding. In an area like the Northwest region of the Río Salado basin, despite the intrinsic 2D characteristics of the overland flow, there are clearly defined paths that water takes that are essentially one-dimensional (such as the interdunal depressions). Consequently, representation of the 2D component (the connections between each longitudinal dune trough) can be limited to simulation of the amount of water that is transferred between these longitudinal paths. The points of connection between adjacent 1D surface water pathways are easily identified by terrain mapping and geomorphic interpretation of the landscape.

Finally it can be concluded that the choice between a 1D hydrodynamic model (like iSIS) or a simpler 2D model (like Lisflood) should depend on striking a balance between the capability of the model to identify surface water drainage pathways and the need to represent surface water hydraulics in detail. The former is also a function of the influence of geomorphic features in conditioning surface flow paths. Generally, a 1D model (like iSIS) can perform adequately provided that the *pattern* of overland flow is known, so that it can be included in the schematisation of the model. A 2D approach would be a better option in those areas where the pattern of preferred pathways cannot be clearly identified *a priori* or where the pattern varies with the event being simulated, making it difficult to encapsulate all the likely runoff scenarios in a single schematisation.

In light of these arguments, and conditions in the Salado Basin, it was concluded that selection of a 3D groundwater model and a 1D hydrodynamic surface water model struck the best balance in terms of the capabilities discussed above. Hence, the following sections describe the development of the coupling between MODFLOW and iSIS Flow (*iSISMOD*).

6.3 The development of *iSISMOD*: Methodological Approach

6.3.1 MODFLOW

MODFLOW is a computer program designed to simulate the three-dimensional movement of water in a saturated porous medium. The program consists of a main program (*"modflow.f"*) and a series of independent subroutines called "modules" that perform the hydraulic computation for each element into which the aquifer system was discretized, such as: abstraction wells, recharge, evapotranspiration, leakage from water bodies, drains, etc.

The period of simulation is divided into a series of "stress periods" within which specified stress parameters are constant. Each stress period can be divided into time steps and the governing equations are solved to give the groundwater head at each node at the end of each time step. Therefore, within a given simulation, there are three, nested loops: a stress-period loop, within which there is a time-step loop, within which there is an iteration loop.

The program performs a series of procedures during a simulation, some of which are performed once for the entire run while others are processed repetitively for each stress period. The procedures carried out for the entire simulation are:

(i) definition of the size of the model, the type of run (steady or unsteady), the calculation of the number of stress periods and the hydraulic elements that will stress the aquifer,

(ii) allocation of memory space to store the data and the results,

(iii) storage of all the data that is not a function of time, including boundary conditions, initial conditions, hydraulic conductivities and geometry of the aquifer.

For each stress period, a further read procedure is processed to store the information that does vary with time, such as pumping rates, recharge, evapotranspiration, etc. Within the iteration loop, a procedure is carried out to calculate the coefficients that are allocated to the matrix that solves the equation of the system. Finally, further post processing procedures are performed to control the output of results and the calculation of the water balance. Appendix B provides details on the structure and governing equations of the program.

6.3.2 iSIS Flow

iSIS Flow is used for modelling steady and unsteady flows in networks of open channels, floodplains and hydraulic structures. Free surface flow is represented by the Saint Venant equations for unsteady flow in open channels.

iSIS is a modular computer program that models the channel network by breaking it down into hydraulic components referred to as units. In addition to channels and floodplains, iSIS contains units to represent a wide variety of hydraulic structures such as sluices, weirs, orifices, storage ponds and head losses through bridges. Flow through closed conduits and culverts are also available through a variety of standard shapes. Model boundaries are represented as either flow-time, stage-time or stage-flow relationships, including tide curves and hydrological boundaries.

The program is basically formed by a core routine that manages the execution of a simulation, a set of routines to perform the hydraulic computation for each type of element (by calculating the coefficients that result from the discretisation of the Saint Venant equations), a routine to solve the resulting matrix, and a set of routines to manage the presentation of results. Appendix B provides details on the structure and governing equations of the program.

6.3.3 iSISMOD

6.3.3.1 Interaction between iSIS and MODFLOW

One of the key aspects of the development is that the structure of iSIS and MODFLOW is preserved. Although iSIS was adopted as the main program, both programs run independently, preserving their own structure for: reading and storing data, calling the various routines that control the different processes and producing the results. All MODFLOW routines were compiled within the iSIS program and the linkage between the two is achieved through the iSIS's core routine (*"ondam.f"*) that calls MODFLOW's main routine (*"modflow.f"*). Figure 6.2 presents the overall approach for the interaction between both programs.

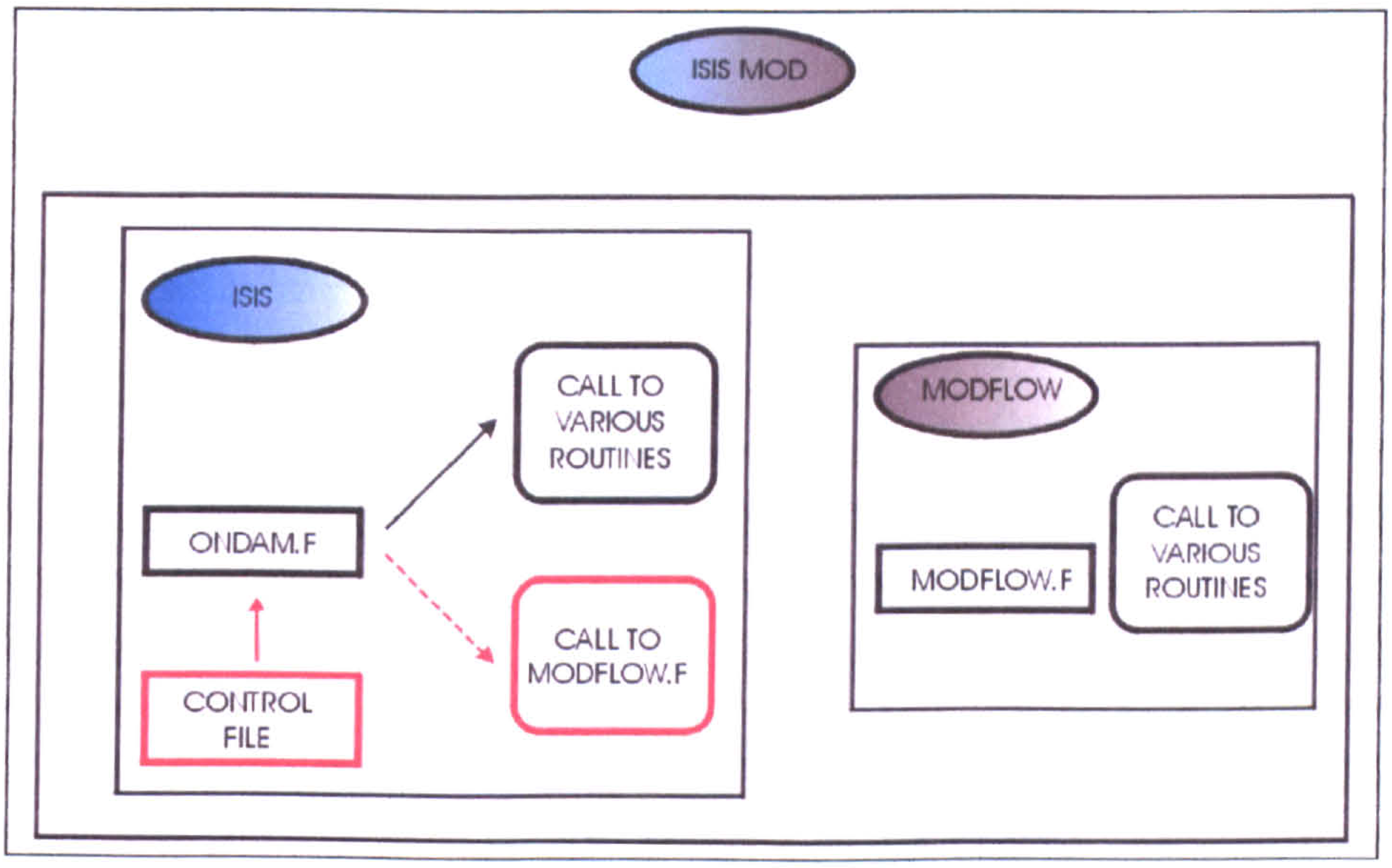


Figure 6.2: iSISMOD Overall Structure

Coupling between the programs is based on the following concept:

MODFLOW solves the groundwater flow equation and provides the groundwater heads that iSIS uses to calculate the corresponding leakage, based on the water level of the surface water body: The leakage is exported back to MODFLOW and the groundwater heads are recomputed. Iteration between programs ceases when the difference between two successive leakage volume calculations is less than a specified tolerance. The issue of the different time steps, normally required for the simulation of both systems independently, was addressed by calculating (in iSIS) an average leakage term during a MODFLOW time step, using groundwater heads linearly interpolated every iSIS time step. The methodology adopted is described below and illustrated in Figure 6.3:

(i) The number of iSIS time steps has to be an integer multiple of the MODFLOW time step. The MODFLOW time step is generally several times larger than the iSIS time step; this is usually the case as there is an inherent difference in the temporal scales of groundwater and open channel dynamics. Time steps of the order of days and months are sufficient for groundwater simulations, while for surface water simulations time steps usually vary from seconds to days.

(ii) iSIS executes a number of time steps equal to a MODFLOW stress period. For each iSIS time step flow, surface water levels and leakage are calculated. In particular, leakage is calculated using a groundwater head that is linearly interpolated from the heads at the beginning and end of the present MODFLOW stress period.

(iii) At the end of a MODFLOW stress period, the leakage calculated for each iSIS time step is averaged and passed to MODFLOW.

(iv) In MODFLOW, the leakage passed from iSIS is used to re-compute the groundwater heads for the current stress period, which are, in turn, passed again to iSIS.

(v) Steps (i) to (iv) are repeated until the average leakage that passes from iSIS to MOFLOW between two successive iSIS-MODFLOW iterations is within a specified tolerance.

In addition, Figures 6.4 and 6.5 illustrate how coupling between the programs is performed.

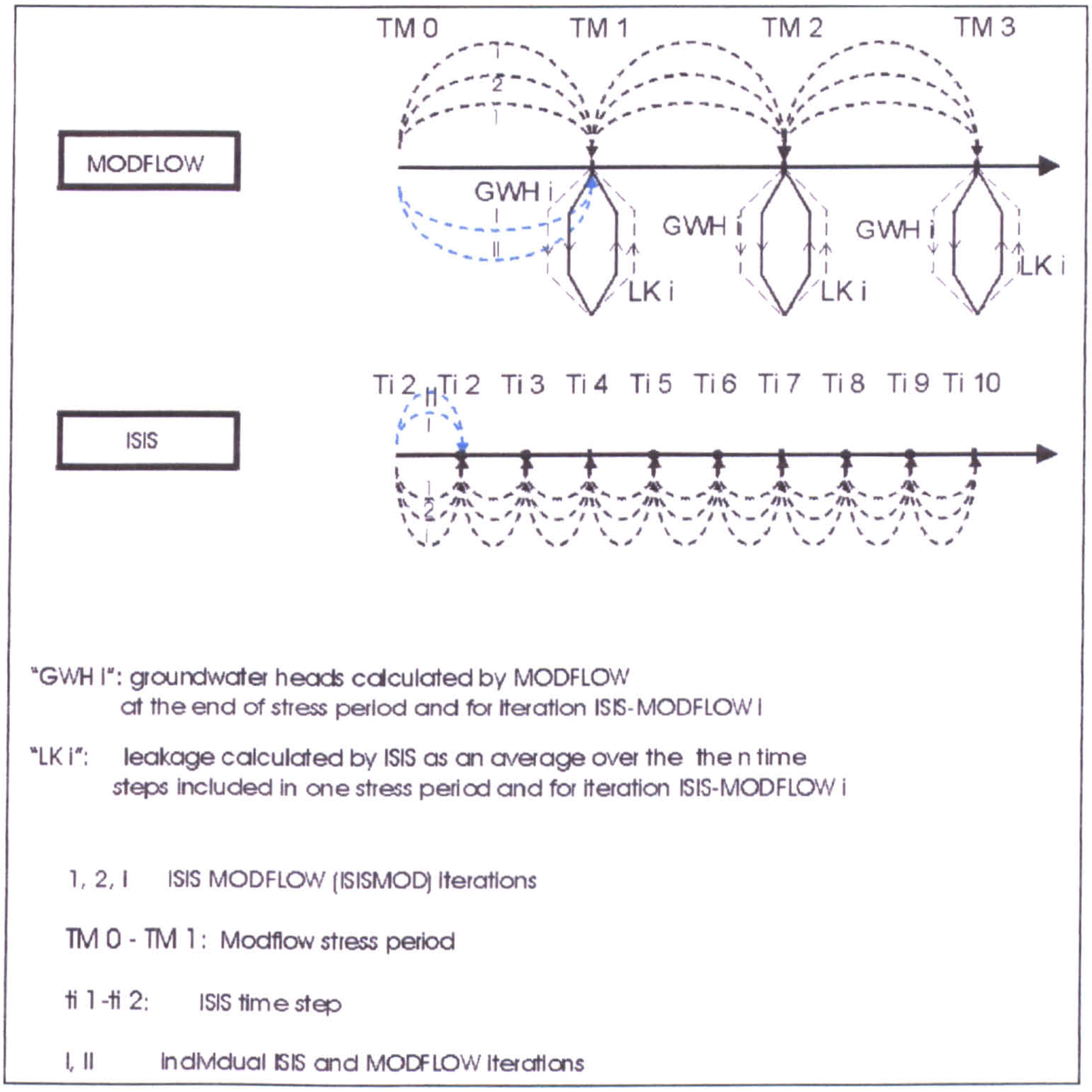


Figure 6.4: iSIS-MODFLOW coupling – Iteration: dealing with varying time steps.

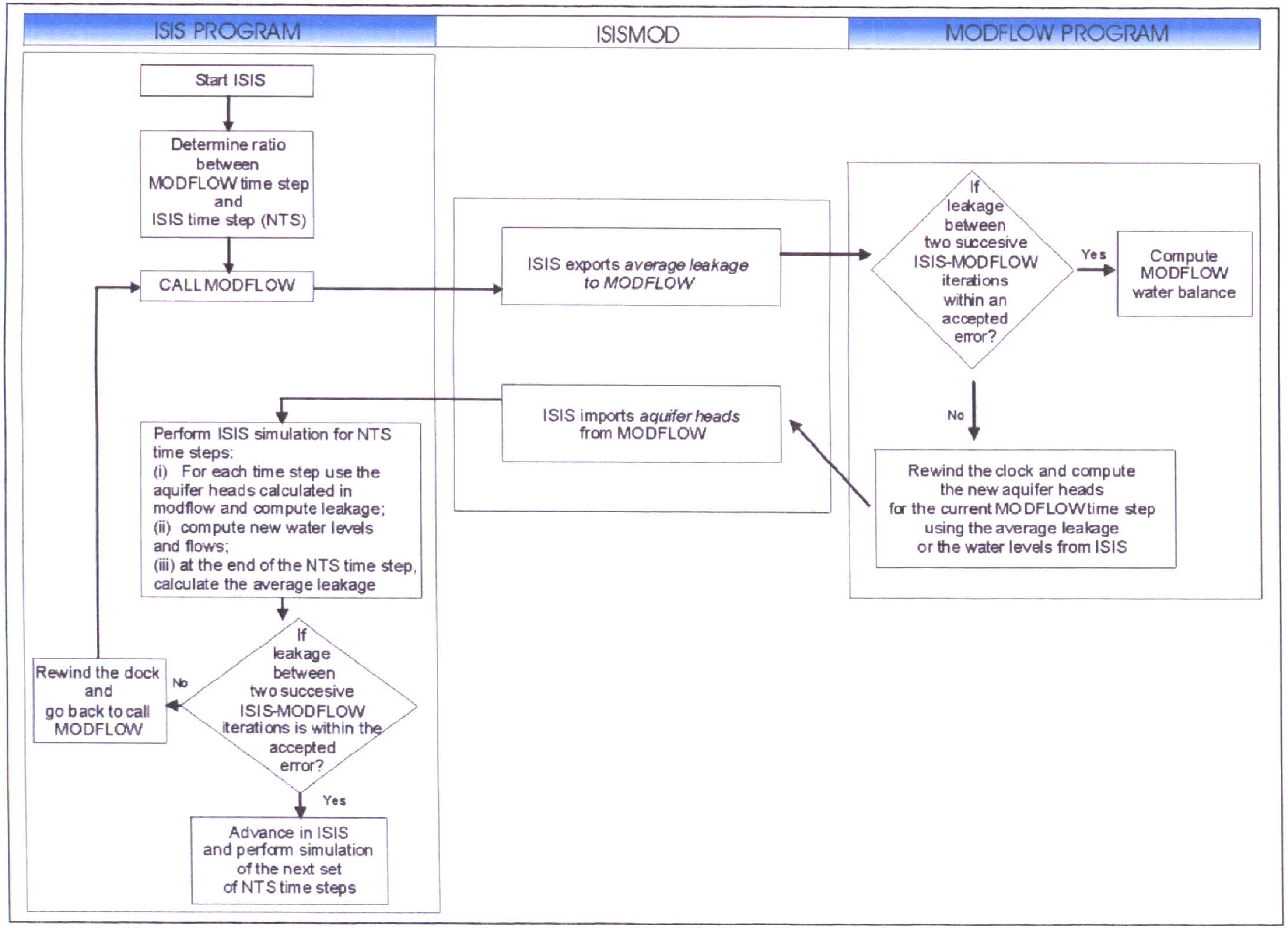


Figure 6.3: iSISMOD – Methodological Approach for the Coupling.

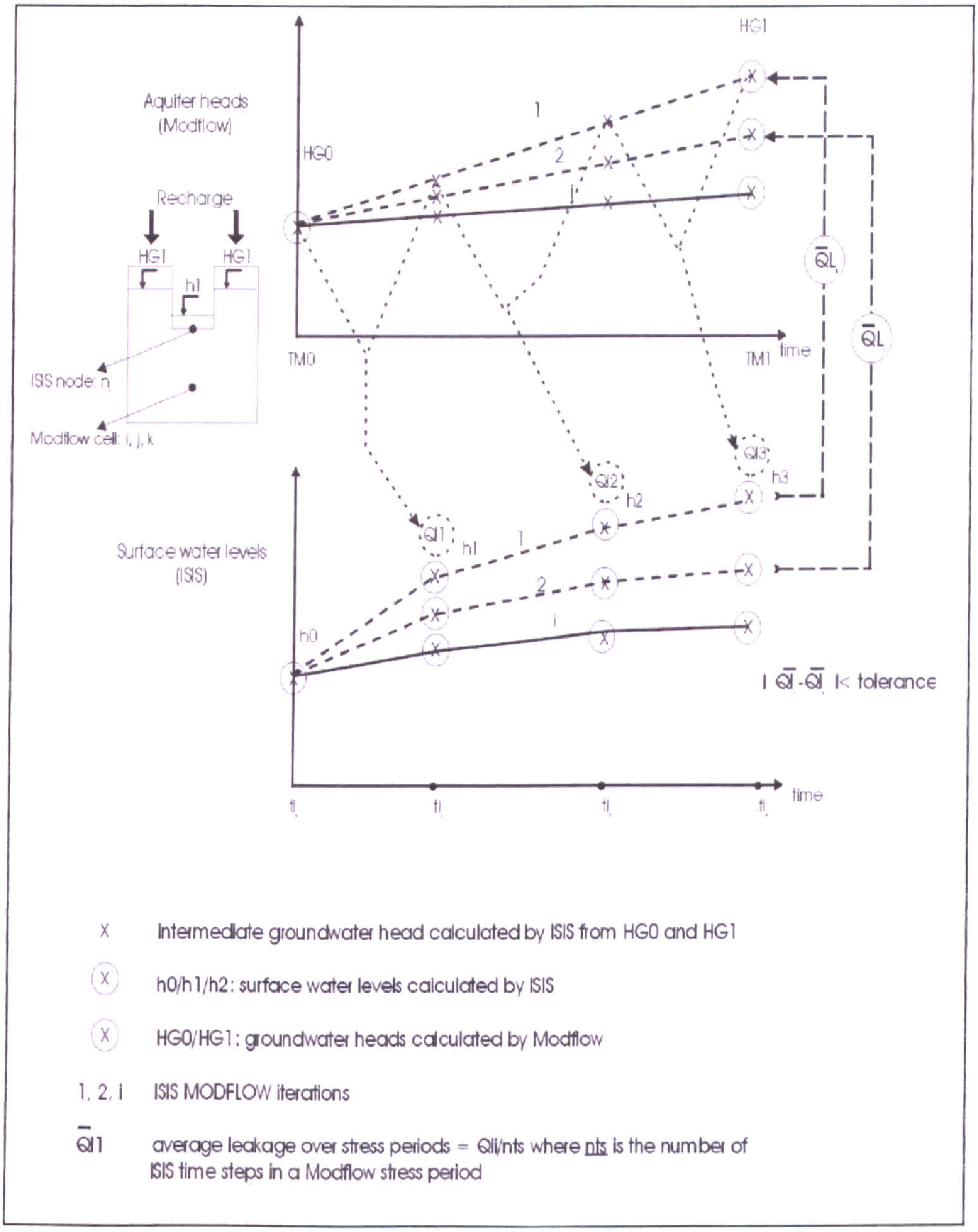


Figure 6.5: iSIS-MODFLOW coupling – Iteration: computing groundwater and surface water heads.

The main changes incorporated into the iSIS program were:

(i) A procedure to implement iSIS-MODFLOW iterations was developed; in iSIS "the clock is reset" to call MODFLOW after each iSIS-MODFLOW iteration was implemented (see Figure 6.4),

(ii) the leakage term was incorporated into the mass equation for the iSIS routines that solves the continuity equation for river channels and reservoirs,

(iii) a control file to store the iSIS labels that interact with the MODFLOW cell nodes and the associated data was created.

The main changes incorporated into the MODFLOW program were:

(i) a new routine was created to export the groundwater heads to iSIS, after computing each stress period,

(ii) another new routine was created to update the continuity equation for the aquifer, with the average leakage calculated in iSIS. This routine was created using a similar structure to the one developed for the Stream package routine (*"str1.f"*), in order to use the data structure already created for the Stream Package as much as possible. This is a key point as allows the user to employ one of the available GIS front ends for MODFLOW (GMS, for example) to create the data file for the STREAM package, that in turn can be used by iSIS.

Finally, Figure 6.6 presents various sample schematics that iSISMOD can handle.

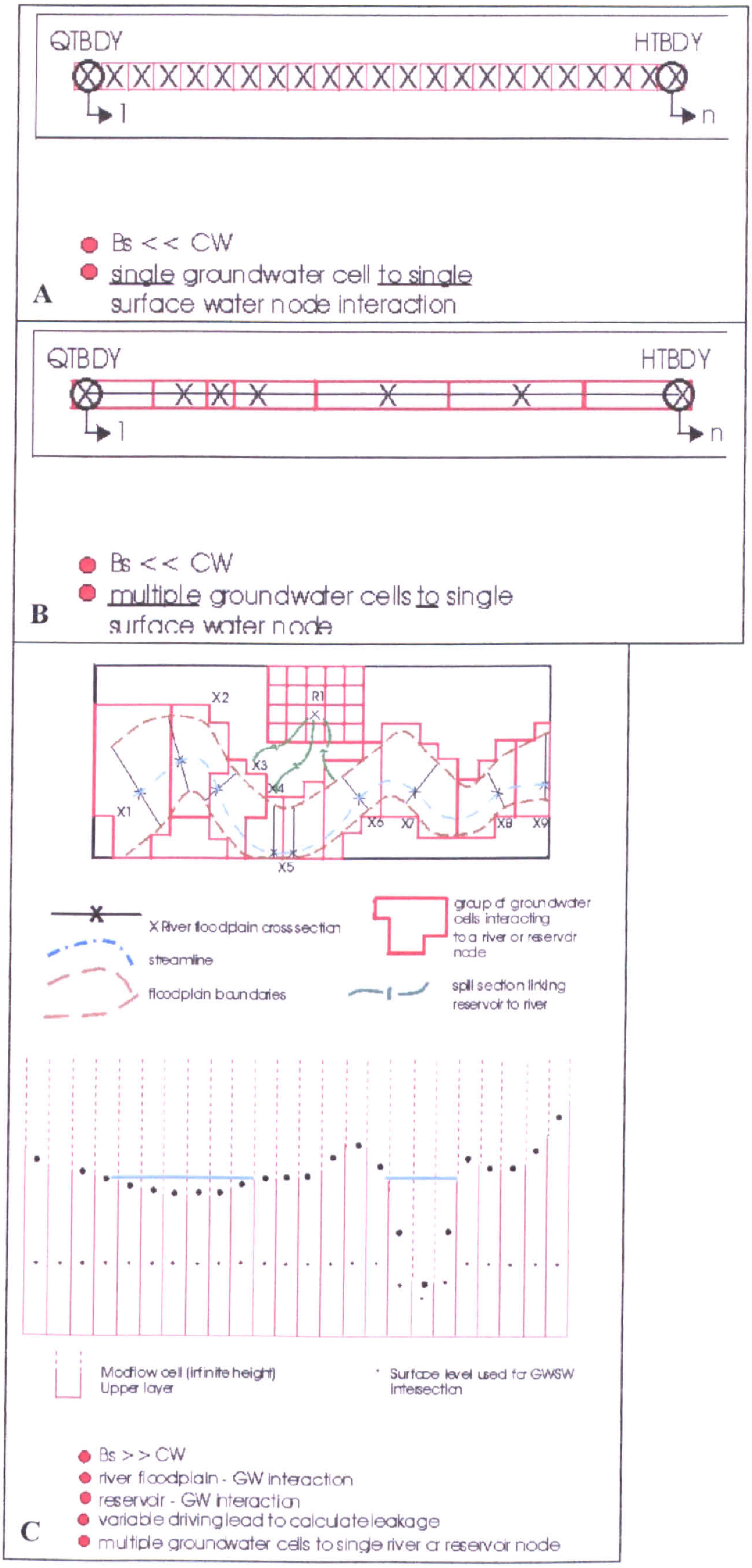


Figure 6.6: A, B and C: sample schematics for iSISMOD simulations

6.3.3.2 Governing Equations

The governing equations for aquifer and surface water interaction are described below. The general expression for the leakage between a stream or a reservoir with an aquifer can be expressed as follows:

$$Ql = \frac{ks}{t} \times L_{area} \times (hs - HGW)$$

where,

Ql = leakage flow that passes between a water body and an aquifer (L^3T^{-1}).

K_s = vertical hydraulic conductivity of the streambed of the water body (LT^{-1}).

t = thickness of the streambed (L).

L_{area} = cross sectional area normal to the leakage flow direction (L^2).

h_s = water elevation of the surface water body (L).

HGW = groundwater head on the aquifer in correspondence with the surface water body (L).

Figure 6.7 conceptualises the parameters used in the above equation.

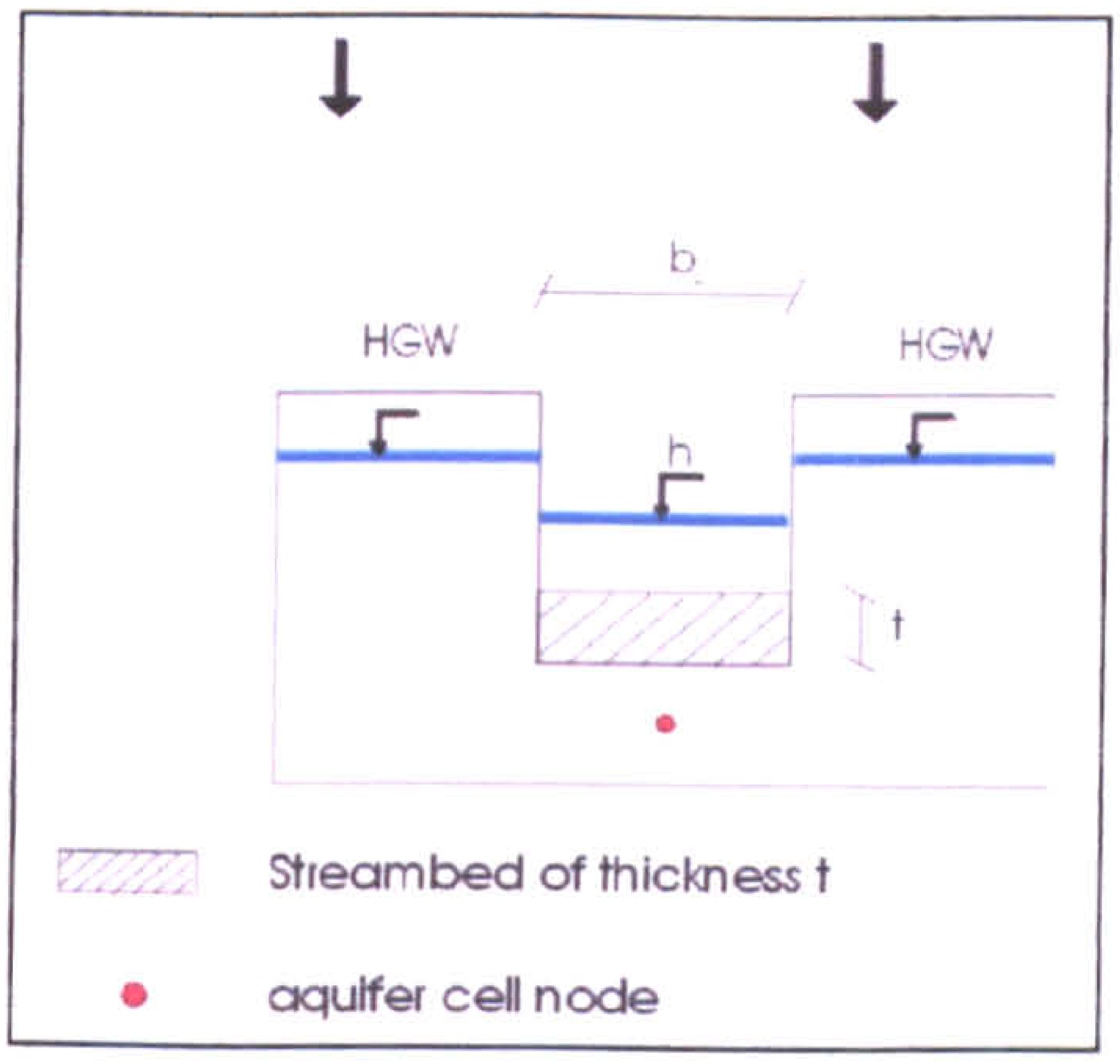
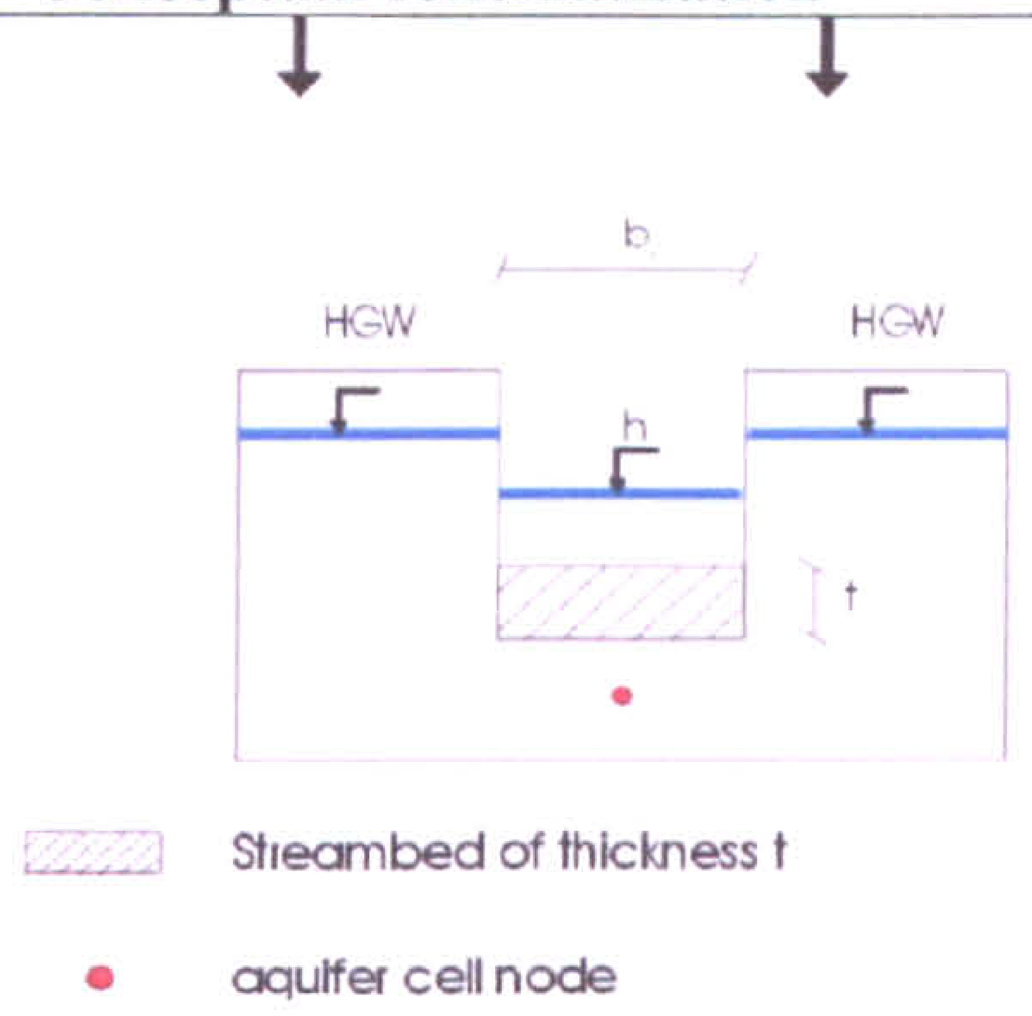


Figure 6.7: Representation of the parameters used in the basic leakage equation.

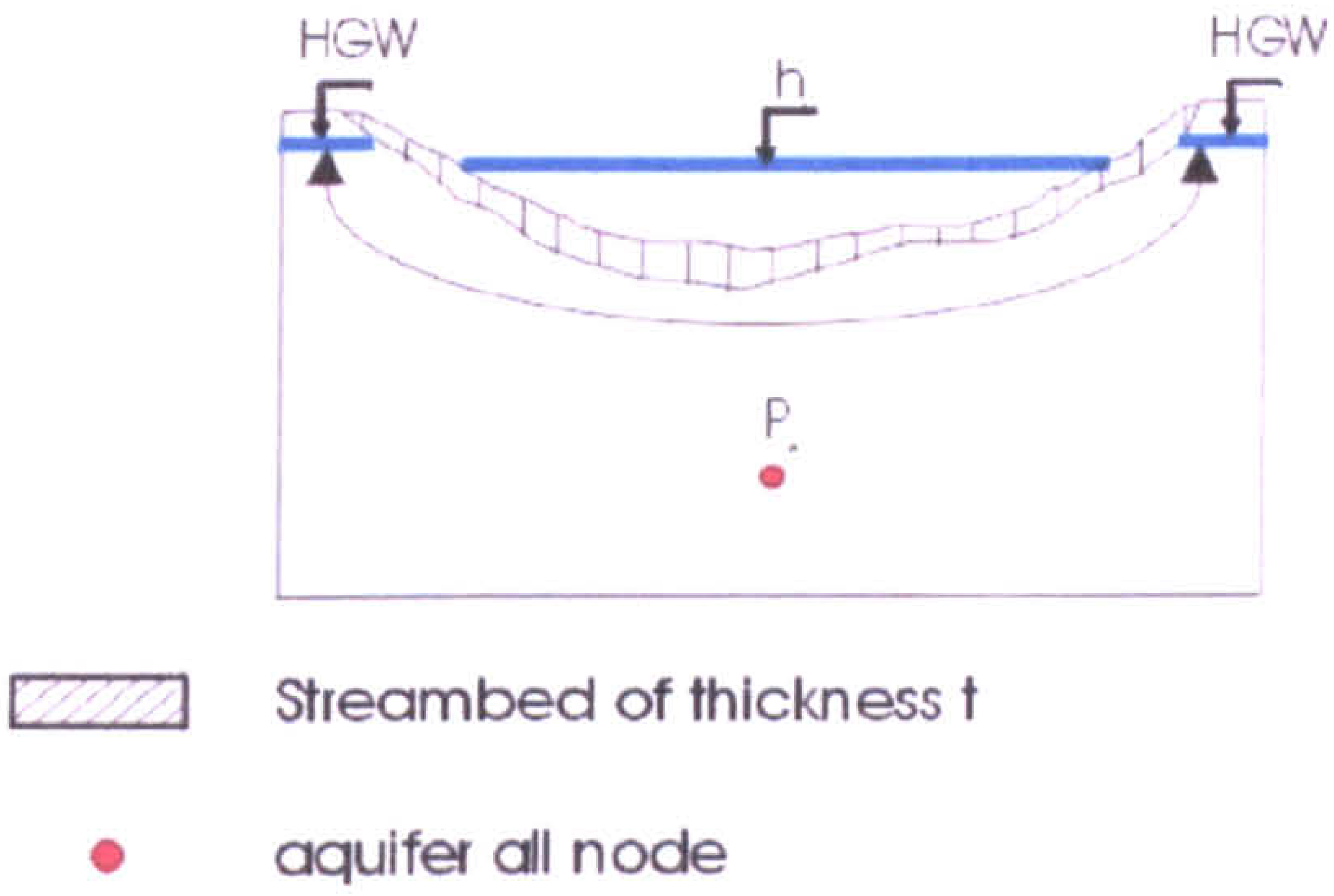
Calculation of L_{area} can be performed in several ways depending on the surface water-groundwater interaction situation, as described in the Table 6.3.

<table>
<tr><th>Description</th><th>Conceptual schematisation</th></tr>
<tr><td>Rectangular channels with a channel width smaller than the aquifer cell width.

$$L_{area} = bs \times dx$$
where,

bs is the channel top width
dx is the distance increment along the surface water flow direction.</td><td>
</td></tr>
<tr><td>Irregular channels with a channel width smaller than the aquifer cell width.

$$L_{area} = Pw \times dx$$
where,

Pw is the wetted perimeter of the channel section. It can be approximated by channel top width if water depth is small.
dx as above.</td><td>
</td></tr>
<tr><td>Irregular channels with a channel width larger than the aquifer cell width.

$$L_{area} = Pw \times dx$$
where,

Pw and dx are as above.

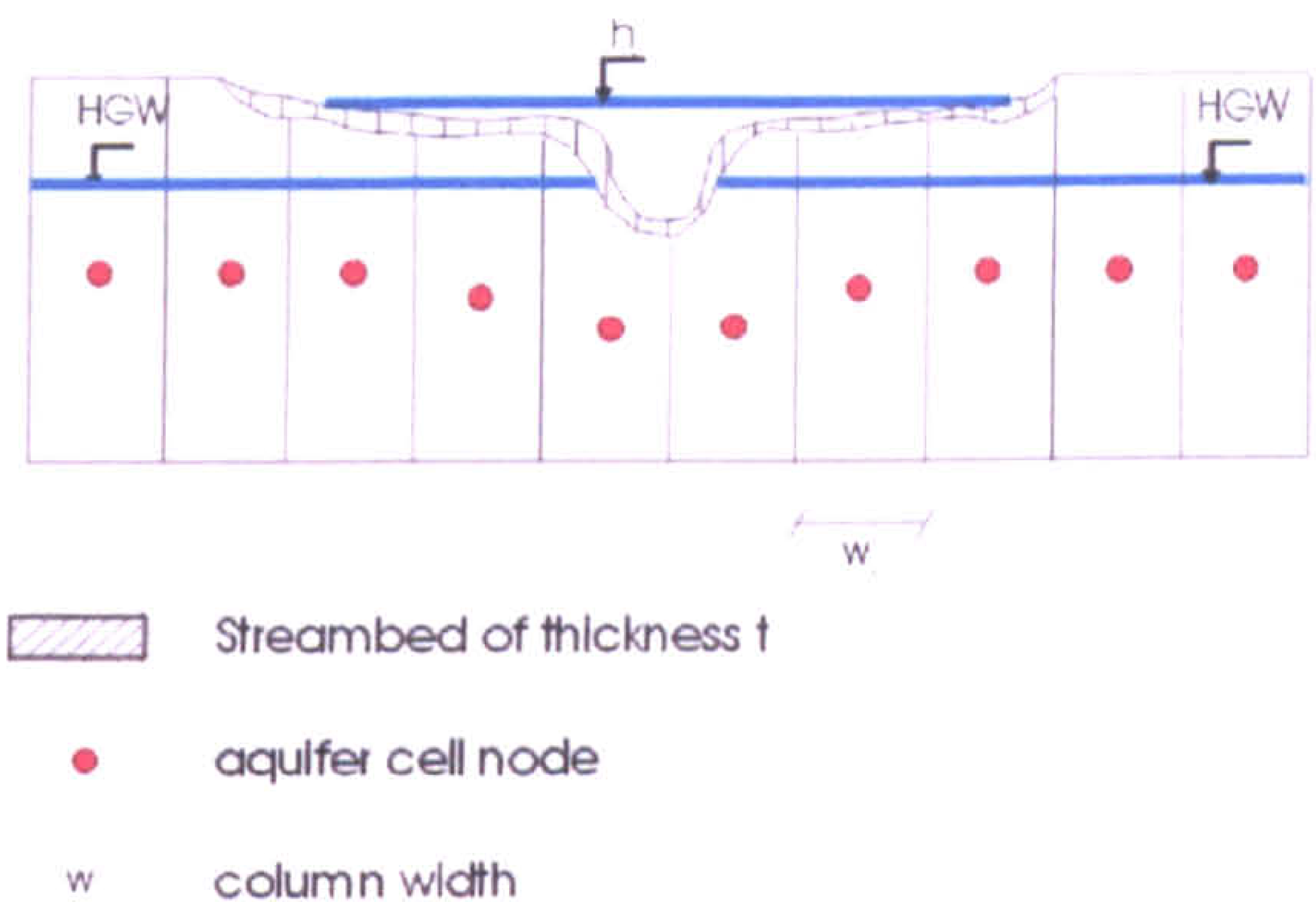
In this case, Pw can be approximated by the aquifer cell width.</td><td>
</td></tr>
</table>

Table 6.3: Examples of calculation of the leakage area.

The resulting continuity equation for open channel, including a leakage contribution from an aquifer, can be expressed as:

$$\frac{\delta Q}{\delta x} + \frac{\delta h}{\delta t} + ql = 0$$

where,

$$ql = \frac{kv \times L_{area} \times (hs - HGW)}{dx}$$

ql = leakage per unit length of channel ($L^3T^{-1}L^{-1}$)

Adopting the finite difference scheme based on the 4-point Preissman approach (see Figure 6.8), each of terms of the continuity equation can be expressed as follows, for the case of multiple aquifer cells interacting to a river reach:

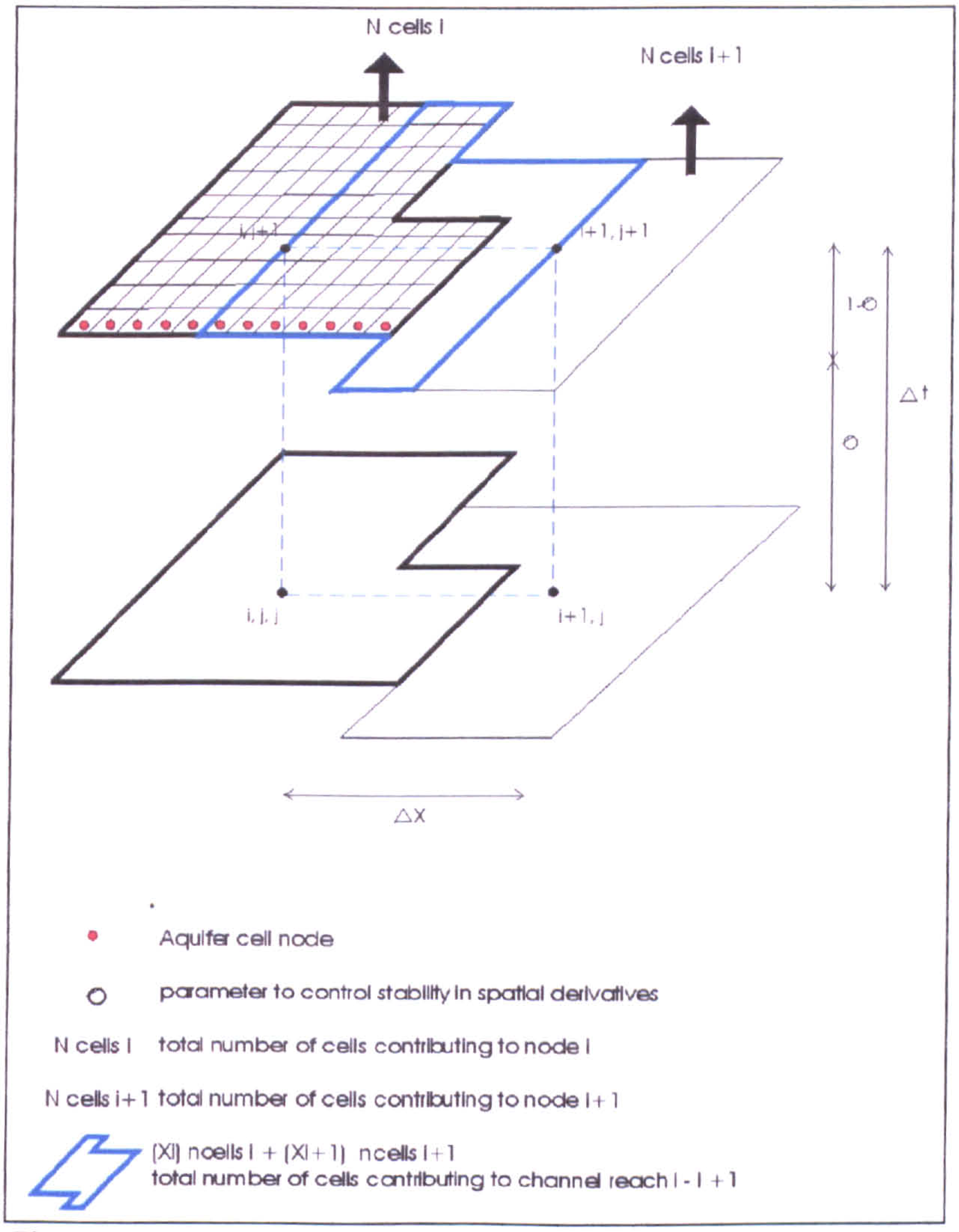


Figure 6.8: Representation of the Preissman scheme for the case of multiple aquifer cells interacting to a river reach.

$$\frac{\partial Q}{\partial x}=\frac{(1-\phi)\times(Q_{i+1}^{j}-Q_{i}^{j})+\phi\times(Q_{i+1}^{j+1}-Q_{i}^{j+1})}{\Delta x}$$

$$\frac{\partial h}{\partial t}=\frac{bs}{2\times\Delta t}\times\left[\left(h_{i}^{j+1}-h_{i}^{j}\right)+\left(h_{i+1}^{j+1}-h_{i+1}^{j}\right)\right]$$

$$ql=\theta\times(\chi_{i+1}\times ql_{i+1}^{j+1}+\chi_{i}\times ql_{i}^{j+1})+(1-\theta)\times(\chi_{i+1}\times ql_{i+1}^{j}+\chi_{i}\times ql_{i}^{j})$$

where,

$$ql_{i+i}^{j}=\frac{1}{\Delta x}\times\sum_{n=1}^{ncells\_2}kv_{n}\times wc_{n}\times wr_{n}\times(h_{i+1}^{j}-HGW_{n}^{j})$$

$$ql_{i}^{j}=\frac{1}{\Delta x}\times\sum_{n=1}^{ncells\_1}kv_{n}\times wc_{n}\times wr_{n}\times(h_{i}^{j}-HGW_{n}^{j})$$

$$ql_{i+i}^{j+1}=\frac{1}{\Delta x}\times\sum_{n=1}^{ncells\_2}kv_{n}\times wc_{n}\times wr_{n}\times(h_{i+1}^{j+1}-HGW_{n}^{j+1})$$

$$ql_{i}^{j+1}=\frac{1}{\Delta x}\times\sum_{n=1}^{ncells\_1}kv_{n}\times wc_{n}\times wr_{n}\times(h_{i}^{j+1}-HGW_{n}^{j+1})$$

where,

bs = open channel surface water width (L)

Δx = distance increment in the open channel network (L)

Δt = time increment for the solution of the open channel network (T^{-1})

ϕ = theta, parameter to control the stability in spatial derivatives.

χ = factor that controls the proportion of aquifer cells that contribute to a specific surface water (iSIS) node.

h = water elevation in a node of the open channel network (L).

HGW = water elevation in the middle of an aquifer cell (L).

ql = leakage flow per unit distance of open channel (L^2T^{-1})

i, i+1 = node counter for the finite difference scheme.

j, j+1 = time counter for the finite difference scheme.

ncells_1= number of total cells assigned to the upstream node of an open channel reach.

ncells_2 = number of total cells assigned to the downstream node of an open channel reach.

n = counter of aquifer cells.

kv_n= vertical conductivity, equal to the hydraulic conductivity divided by streambed thickness (T^{-1}).

wc_n= column width (L).

wr_n= row width (L).

Rearranging terms, the continuity equation can be expressed as a linear function as follows:

$$a2 \times Q_i^{j+1} + b2 \times h_i^{j+1} + c2 \times Q_{i+1}^{j+1} + d2 \times h_{i+1}^{j+1} = r1$$

where,

$$a2 = -\frac{\theta}{\Delta x}$$

$$c2 = \frac{\theta}{\Delta x}$$

$$b2 = \frac{bs}{2 \times \Delta t} + \frac{\theta}{\Delta x} \times \chi_i \times \sum_{n=1}^{ncells\_1} kv_n \times wc_n \times wr_n$$

$$d2 = \frac{bs}{2 \times \Delta t} + \frac{\theta}{\Delta x} \times \chi_{i+1} \times \sum_{n=1}^{ncells\_2} kv_n \times wc_n \times wr_n$$

$$r1 = -\frac{(1-\theta)}{\Delta x}\times(q_{i+1}^{j} - q_i^{j}) + \frac{bs}{2\times\Delta t}\times(h_i^{j} + h_{i+1}^{j}) -$$
$$\frac{(1-\theta)}{\Delta x}\times\chi_{i+1}\times\sum_{n=1}^{ncells\_2} kv_n \times wc_n \times wr_n \times(h_{i+1}^{j} - HGW_{i+1}^{j}) -$$
$$\frac{(1-\theta)}{\Delta x}\times\chi_{i}\times\sum_{n=1}^{ncells\_1} kv_n \times wc_n \times wr_n \times(h_{i}^{j} - HGW_{i}^{j}) +$$
$$\frac{(\theta)}{\Delta x}\times\chi_{i+1}\times\sum_{n=1}^{ncells\_2} kv_n \times wc_n \times wr_n \times HGW_{i+1}^{j+1} +$$
$$\frac{(\theta)}{\Delta x}\times\chi_{i}\times\sum_{n=1}^{ncells\_1} kv_n \times wc_n \times wr_n \times HGW_{i}^{j+1}$$

The iSIS routine that solves the equations for the river channel, computes the contributing terms to the coefficients that are finally assigned to the matrix for each iSIS node and for each aquifer cell.

The mass transferred between an aquifer and a stream body, calculated according to the Darcy's equation, is usually of very low velocity compared to the open channel flow along a river system and, therefore, the contribution to the overall momentum of the system is small. As a result, the momentum equation was not modified for the current development of iSISMOD.

A leakage term was also included in the routine of iSIS that solves the accumulation of storage into a reservoir. The equation can be expressed as:

$$h_i^{j+1} = h_i^{j} - \frac{Ql\times\Delta t}{Area} + \frac{qnet\times\Delta t}{Area}$$

where,

$qnet$ = summation of all inflows to the reservoir (L^3T^{-1}).

h^{j+1} = water level in the reservoir node (i) at time j+1 (L).

h^{j} = water level in the reservoir node (i) at time j (L).

Ql = total leakage flow (L^3T^{-1})

Δt = time increment (j+1-j) (T^{-1})

Area = reservoir area, as an average between the current and the previous time step (L^2)

The leakage is calculated using:

$$Ql = \theta \times Ql_i^{j+1} + (1-\theta) \times Ql_i^j$$

where,

Ql^{j+1} = total leakage at the current time step, calculated as the summation of the leakage from the individual cells.

Ql^{j} = total leakage at the previous time step, calculated as the summation of the leakage from the individual cells.

θ = a parameter (0-1) to control stability of the solution.

The continuity equation expressed in linear form results:

$$cf1 \times h_i^{j+1} + \sum_{n=1}^{ninflows} q_n^{j+1} = r1$$

where,

ninflows denotes the number of flows entering (positive sign) or leaving (negative sign) the reservoir

The resulting coefficients for the matrix (in the same way as it was calculated for the river unit) are:

$$cf1 = \frac{abar}{\Delta t} + \theta \times \sum_{n=1}^{ncells} kv_n \times wr_n \times wc_n$$

$$cf2 = -1 \times \theta$$

$$cf3 = 1 \times \theta$$

$$r1 = h_i^j \times \frac{abar}{\Delta t} + \theta \times \sum_{n=1}^{ncells} kv_n \times wr_n \times wc_n \times HGW_n^{j+1}$$
$$-(1-\theta) \times \sum_{n=1}^{ncells} kv_n \times wr_n \times wc_n \times (h_i^j \times HGW_n^j)$$

where,

kv_n=	vertical conductivity, equal to the hydraulic conductivity divided by streambed thickness (T^{-1}).
wc_n=	column width (L).
wr_n=	row width (L).

Continuity equation – MODFLOW

Solution of the continuity equation in MODFLOW is also achieved in finite difference form, but this does not use the 4-point Preissmann scheme applied in iSIS. In MODFLOW the theta parameter to control stability in spatial derivatives is not used and a fully forward scheme is used to calculate the derivative in time.

For a cell *i,j,k,* the continuity equation in finite difference form is expressed as:

$$CR_{i,j-1/2,k} \times (h^m{}_{i,j-1,k} - h^m{}_{i,j,k}) + CR_{i,j+1/2,k} \times (h^m{}_{i,j+1,k} - h^m{}_{i,j,k})$$
$$+CC_{i-1/2,j,k} \times (h^m{}_{i-1,j,k} - h^m{}_{i,j,k}) + CC_{i+1/2,j,k} \times (h^m{}_{i+1,j+1,k} - h^m{}_{i,j,k})$$
$$+CV_{i,j,k-1/2} \times (h^m{}_{i,j,k-1} - h^m{}_{i,j,k}) + CV_{i,j,k+1/2} \times (h^m{}_{i,j,k+1} - h^m{}_{i,j,k})$$
$$+P_{i,j,k} \times h^m_{i,j,k} + Q_{i,j,k} = SS_{i,j,k} \times (\Delta rj \times \Delta ci \times \Delta vk) \times \frac{(h^m_{i,j,k} - h^{m-1}_{i,j,k})}{(t_m - t_{m-1})}$$

where,

CR, CC and CV	= the conductance terms in the row, column and layer direction.

m, m-1	indicates time counter.
Δrj, Δci, Δvk	= the cell dimensions (row, column, layer thickness).
SS	= specific storage.
P and Q	= the summation of the terms from the equations that define the contribution from external sources to the given cell.

For the solution of the above equation, it is convenient to arrange it so that all terms containing heads at the end of the current time step are grouped on the left hand side of the equation, whereas all terms independent of head at the end of the current time step are on the right hand side of the equation. The resulting equation and coefficients are:

$$
\begin{aligned}
& CR_{i,j-1/2,k} \times h^{m}{}_{i,j-1,k} + CC_{i-1/2,j,k} \times h^{m}{}_{i-1,j,k} + CV_{i,j,k-1/2} \times h^{m}{}_{i,j,k-1} \\
& +(-CV_{i,j,k-1/2} - CC_{i-1/2,j,k} - CR_{i,j-1/2,k} - CR_{i,j+1/2,k} - CC_{i+1/2,j,k} \\
& -CV_{i,j,k+1/2} + HCOF_{i,j,k}) \times h^{m}_{i,j,k} + CR_{i,j+1/2,k} \times h^{m}_{i,j+1,k} + CC_{i+1/2,j,k} \times h^{m}_{i+1,j,k} \\
& +CV_{i,j,k+1/2} \times h^{m}{}_{i,j,k+1} = RHS
\end{aligned}
$$

where,

$$HCOF_{i,j,k} = P_{i,j,k} - \frac{SC1_{i,j,k}}{(t_m - t_{m-1})}$$

$$RHS_{i,j,k} = -Q_{i,j,k} - \frac{SC1_{i,j,k} \times h^{m-1}_{i,j,k}}{(t_m - t_{m-1})}$$

$$SC1_{i,j,k} = SS_{i,j,k} \times \Delta rj \times \Delta ci \times \Delta vk$$

MODFLOW, by calling the routines associated to each of the modules (river, recharge, evapotranspiration, etc.) calculates the cumulative contribution (for each iteration within a time step) to the HCOF and RHS terms.

As the leakage is calculated in iSIS, the treatment in MODFLOW is explicit and the modifications to the corresponding coefficients are:

$$HCOF(II,JJ,KK) = HCOF(II,JJ,KK)$$

$$RHS(II,JJ,KK) = RHS(II,JJ,KK) - FLOBOT(II,JJ,KK)$$

where,

FLOBOT	= average leakage calculated in iSIS expressed in the time units used in MODFLOW to define the stress periods.
II,JJ,KK	= the indexes to represent the row, column and layer of each cell.

6.3.3.3 Output Files

The results of a run performed using iSISMOD can be examined using the standard graphic interfaces of each of the individual iSIS and MODFLOW programs. However both programs were modified to present the relevant information generated by iSISMOD.

iSIS can be used to examine surface water levels in rivers and reservoirs in the usual way but, for those units coupled to MODFLOW, an option was included to show other variables such as: reservoir/river-average groundwater level, reservoir/river-average ground level and reservoir/river cumulative leakage.

MODFLOW output file (*"filename.out"*) was also modified to include a leakage term (from iSIS) in the overall volumetric budget at the end of each stress period, adopting the same convention as the one used by the STREAM and RIVER packages. A caption of an output file is presented in Figure 6.9.

To facilitate processing on a grid (raster) basis, iSISMOD writes to a file, for each stress period, the surface water level associated to each cell interacting with iSIS. When the groundwater head is below the ground surface, the latter is the value written to the cell. Finally, if the cell does not interact with any iSIS unit, then iSISMOD writes the corresponding groundwater level for the cell.

```
                              VOLUMETRIC BUDGET FOR ENTIRE MODEL AT END OF TIME STEP  1 IN STRESS PERIOD120
                              ---------------------------------------------------------------------------
0                   CUMULATIVE VOLUMES      L**3                                  RATES FOR THIS TIME STEP      L**3/T
                    ------------------                                            ------------------------

                          IN:                                                               IN:
                          ---                                                               ---
                            STORAGE =    0.50660E+06                                          STORAGE =    491.68
                      CONSTANT HEAD =    0.00000E+00                                    CONSTANT HEAD =    0.00000E+00
                      ISIS  LEAKAGE =    0.76591E+06                                    ISIS  LEAKAGE =    0.00000E+00
0                          TOTAL IN =    [illegible]                                         TOTAL IN =    [illegible]
0                        OUT:                                                              OUT:
                         ----                                                              ----
                            STORAGE =    0.10106E+07                                          STORAGE =    47.855
                      CONSTANT HEAD =    0.00000E+00                                    CONSTANT HEAD =    0.00000E+00
                      ISIS  LEAKAGE =    0.26193E+06                                    ISIS  LEAKAGE =    443.89
0                         TOTAL OUT =    [illegible]                                        TOTAL OUT =    [illegible]
0                          IN - OUT =     6.3750                                             IN - OUT =   -0.70526E-01
0               PERCENT DISCREPANCY =                 0.00                        PERCENT DISCREPANCY =               -0.01


0

          TIME SUMMARY AT END OF TIME STEP  1 IN STRESS PERIOD120
                                   SECONDS          MINUTES          HOURS            DAYS             YEARS
                              -----------------------------------------------------------------------------------
      TIME STEP LENGTH             300.000          5.00000          0.833333E-01     0.347222E-02     0.950643E-05
    STRESS PERIOD TIME             0.000000E+00     0.000000E+00     0.000000E+00     0.000000E+00     0.000000E+00
 TOTAL SIMULATION TIME             36000.0          600.000          10.0000          0.416667         0.114077E-02
1
```

Figure 6.9: Volumetric budget at the end of an iSISMOD simulation. Note that the term "iSIS Leakage" was added in the balance.

Finally a series of files are created after each iSISMOD run:

(i) a diagnosis file (*"iSISMOD.rep"*) that reports the following information:

- leakage for each iSIS node, for each time step and stress period
- leakage for each MODFLOW cell, for each stress period
- the number of iSIS-MODFLOW iterations used to solve each stress period and the final mass balance convergence achieved.

(ii) several time series files created from the *"filename.plt"* file. These files contain groundwater or surface water levels for each time step or stress period for various predefined configurations (long sections, cross sections or individual cells)

6.4 Testing of the iSISMOD

A series of tests was carried out to check the correct functioning of iSISMOD. For all test cases, the results obtained with iSISMOD were compared to either an independent data source or with a hand calculation. The tests carried out are summarised below:

Test Case 1: single reservoir-aquifer interaction through a single and multiple MODFLOW cells.

Test Case 2: single river-aquifer interaction in a steady state situation.

Test Case 3: combined river and reservoir interaction with an underlying aquifer.

Test Case 4: flood wave attenuation along a river channel due to bank storage effects.

Test 4 is one of the most representative test cases as it permits to test iSISMOD for simulating the dynamic interaction between a surface and a groundwater system. A description of this test and its results obtained are summarised below while a Appendix B presents a full description of all cases carries out.

Test 4 aims at simulating the bank attenuation effect that results from the GW-SW interaction when a flood wave passes along a stream, similarly to what has been solved numerically by Pinder and Sauer (1971). An iSISMOD run was performed using the same data used in that paper and results compared to those obtained by those authors.

The iSIS data file consisted of a single channel 51580m long with nodes at 610m spacing and a 30.48m cross section width at each node. The inflow hydrograph was a cosine function with an initial value of 510cumecs.

The MODFLOW model consisted of an unconfined aquifer represented by a single layer with an aquifer storativity/specific yield of 0.25 and a permeability of 263.3m/day. The grid was characterised by a vertical spacing of 610m (in the direction of the stream) and a horizontal spacing of 30m everywhere except near either bank of the stream where the spacing was reduced to 15m.

Figures 6.10 shows that iSISMOD can reproduce the results obtained by Pinder and Sauer (1971), in terms of the effect of SW-GW interaction in flood wave attenuation due to bank storage effect. Smaller differences can be noticed, which could be originated when digitising the hard copy results of Pinder and Sauer (1971), or from the mathematical solver used.

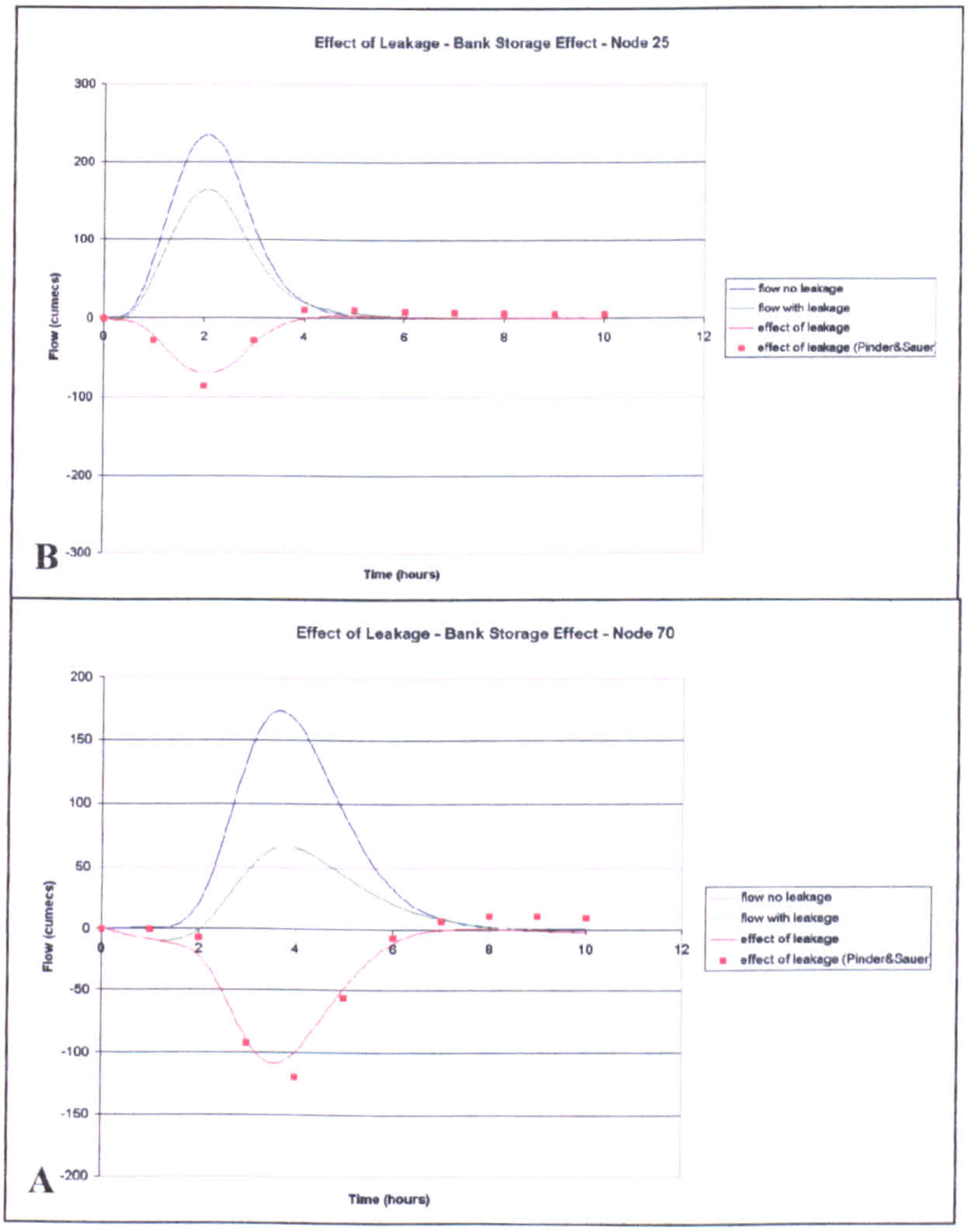


Figure 6.10: Effect of leakage in a node located 50,000ft (A) and 140,00ft (B) from the beginning of the channel.

- CHAPTER 7 -

iSISMOD APPROACH

7.1 Introduction and Approach

This chapter describes the application carried out with iSISMOD on the test area described in Chapter 3, in order to assess advantages and disadvantages of using a coupled model to generate FPMs, in comparison to the use of MODFLOW alone.

A similar approach to that adopted in Chapter 5 was followed to analyse the applicability of iSISMOD: predicted surface water levels along longitudinal and cross sectional profiles in the dune field were examined in comparison to flooded areas identified by the model and those obtained through interpretation of satellite imagery.

Historical simulations for the wettest period that took place in the test area region (1985-1990) and 33years (baseline) simulations were carried out. The latter were used to generate the base and project FPMs.

7.2 Schematisation of the Test Area Model using iSISMOD

7.2.1 Location of Test Area Model

The test area lies within the Northwest region of the Salado basin, having as distinct features a predominance of dune fields and the lack of a fluvial drainage system to convey the excess generated by groundwater induced flooding events. The location and characteristics of the test area were described in detailed in Chapter 3.

7.2.2 Schematisation of the Test Area Model (TAM) using iSISMOD

The overall schematisation of the TAM using iSISMOD consists of schematisation of the groundwater component (layer 2) and the surface water component (layer 1).

For layer 2, schematisation follows the concepts and parameters used for development of the RGWM as it takes its boundary conditions (groundwater heads) from the latter. However, based on the experience gained through examining the simulations carried out with the RGWM and the need to develop a computationally more efficient model with a higher spatial resolution, a simplification was made in terms of its vertical conceptualisation.

While the RGWM comprised three layers in the vertical dimension, representing the formations found to be within the hydrogeologically active part of the aquifer (Chapter 3), for the TAM a single layer was included to represent only the sand layer immediately below the ground surface. The technical justification for this simplification is based on the following facts:

- horizontal conductivities of the layers underneath the sand dune field are very low (less than 1m/d compared to the range of conductivities in the top sand layer of up to 10m/d), and the vertical conductivity between the layers does not exceed 0.01m/d, and

- groundwater levels oscillate within the sand layer with amplitudes that do not exceed 4m or 5m and are, most of the time, close to the ground surface. These levels would be hardly influenced by vertical leakage from and to the layers below the sand.

The horizontal discretisation of the model was carried out using cells of 500m by 500m, instead of the 5000m grid used in the RGWM. This is consistent with what was initially found in Chapter 5 in terms of the convenience of having a groundwater model grid that matches the resolution of the DEM for an adequate identification of flooding in the surface.

Detailed analysis of the characteristics of the soils in the test area reveals the existence of thin layers of low permeability soils (known as "B horizons") underlying the depressions along the longitudinal interdunes. These are mainly formed by the semi-permanent presence of water in those low areas that contribute to the infiltration and deposition of fine material. The effect of these soil formations could be schematised through the spatial variation of the vertical hydraulic conductivity (kv) that was used to control the transfer of water between the sand layer (aquifer model) and the ground surface.

The hydrogeological parameters used for the TAM are those of the sand (top) layer of the RGWM aquifer model as presented in Table 7.1. Figures 7.1 and 7.2 present the schematic of the TAM with iSISMOD.

Parameter	**Value**
Horizontal hydraulic conductivity.	5 (m/day)
Vertical hydraulic conductivity between the aquifer and the open surface.	0.1(m/day)
Specific yield.	0.1 (-)

Table 7.1: Hydrogeological Parameters used in the TAM

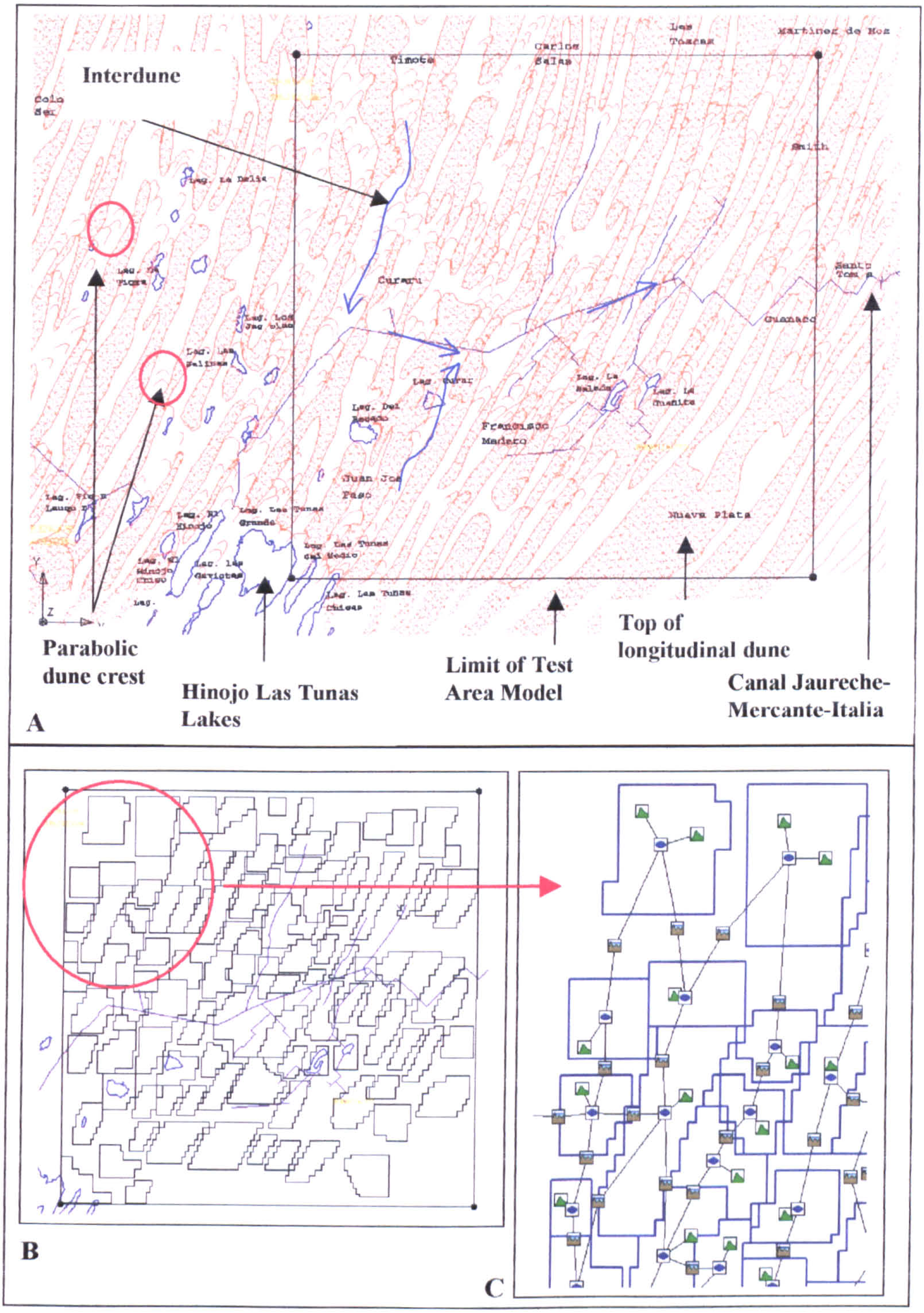


Figure 7.1: Schematisation of test area model. **A**: plan view of dune field and drainage system. **B**: flood cells. **C**: iSIS reservoir and spill units in a portion of the model.

The surface water component of the model (layer 1) was schematised to reproduce as closely as possible the mechanisms that operate at the surface due to the occurrence of groundwater-induced flooding and waterlogging. Those mechanisms are:

(i) Exfiltration of water at the surface, due to groundwater phreatic levels emerging at the surface;

(ii) Ponding of exfiltrated water behind parabolic dunes and/or spread of water over low areas in the troughs between large, longitudinal dunes throughout the region;

(iii) Transfer of water from one low area to another low area, once the topographic threshold created by the crest heights of the parabolic dunes is exceeded, creating occasional major streams of water;

(iv) Transfer of water from low areas to existing drainage infrastructure (canals) and flooding due to the lack of conveyance capacity of the canals;

(v) Saturation overland flow as rainfall falls onto a variable area of saturated ground;

(vi) Seasonal expansion/contraction of open surface water bodies, whose areas vary dynamically, as a function of rainfall and evaporation.

Points (i), (v) and (vi) lead to the concept of variably contributing areas for runoff.

Layer 1 of the model was schematised using the units available in iSIS Flow. Two approaches emerged as options to model ponding and transfer of water from one low area to another. Approach A consists of using reservoir units (or flood cells) to simulate the movement of ponded water connected to each other using control sections such as irregular weirs (known as "spill" units in iSIS) to govern the transfer of water. An alternative to the use of the spill units is to use the iSIS Floodplain Sections that allow calculation of the flow from one cell to the next downstream using a normal depth type of formula like Manning's equation. Approach B consists of simulating both ponding and transfer, in a single unit, making use of river sections to model the conveyance of water along the axis of the interdunal depressions. The river sections would have to extended either side to cover the entire flood extent. Table 7.2 summarises advantages and disadvantages of each approach.

Approach	Advantages	Disadvantages
A _1 (Reservoirs + Spills)	• Faster convergence • Simulates better the appearance of water on the surface. • Easier to set up. • Less data intensive. Needs stage area curves for each flood cell and the approximate section that controls the passage of water downstream.	• Provides only a water level for each reservoir, ignoring sloping effects on long interdunal depressions that are lumped in flood cells. • Underestimates the time of travel and attenuation of the water moving downstream as the resistance part of the open channel equations is not simulated.
A _1 (Reservoirs + Floodplain sections)	• Preserves the advantages describe above for the use of reservoirs but the transfer of flow between cells is better represented as it used a Manning equation for uniform flow, based on a water slope calculated from the water level of each cell and the distance that separates one from the other	• Still only provides a single water level for each cell. • The time of travel is not properly reproduced with this option either as dynamic effects are ignored.
B (River)	• Provides a more accurate longitudinal water level profile along an interdunal depression. • More suitable for the simulation and analysis of drainage works (i.e. canals).	• Convergence is more difficult to achieve, in particular for low flows. • Therefore, this approach is less suitable for simulating the appearance of water on the surface, requiring additional considerations to stabilize the model, such as the use of small dummy flows or the use of the Preissman slot facility. • More data demanding, requiring cross sections of the interdunal depressions at variably distance steps depending on the variation of the bed profile.

Table 7.2: Surface Water System: modelling approaches.

The approaches are not necessarily mutually exclusive and could be combined depending on the characteristics of the area to be modelled. In a practical application, Approach A would be suitable for the simulation of baseline and calibration scenarios, while Approach B would be better suited to simulating a proposed drainage scheme.

The test area is crossed by a drainage canal (Jaureche-Mercante) built in the late 1980s as a consequence of the major flood event on the region, which took place in 1987/1988. The canal was simulated as an open channel, with its origin in the lake complex of Hinojo-Las Tunas, finishing several kilometres outside the test area.

The inflow to the TAM was provided, as it was for the case of the RWGM, by the rainfall-runoff model HYSIM. Inflow comprised daily time series of either rainfall or infiltration and potential evapotranspiration. In the RGWM, the transfer of lumped infiltration and evapotranspiration time series to each cell of the model was carried out fitting a surface, month by month, using the monthly values provided by HYSIM for each of the sub-catchments in which the entire Salado basin was discretised. Because the entire test area fell within a single HYSIM sub-catchment, no interpolation was carried out and the same catchment monthly values were assigned to all of the model cells.

In the absence of any physical divide within the Northwest region, the boundaries of the test area model were determined to cover a wide range of geomorphic features, such as the interdunal depressions, in order to model surface flow coming from the North and the South of the Canal Jauretche-Mercante. For layer 2 (the aquifer), variable groundwater levels were specified for each cell along the boundaries of the test area. These heads were taken from the results obtained from the simulations carried out with the RGWM, resampled accordingly to match the resolution (500m) of the TAM.

For layer 1 of the TAM, a nominal inflow was specified as entering the Hinojo-Las Tunas reservoir at the upper boundary of the Jaureche-Mercante canal system. The downstream boundary for this canal was specified as a head-discharge relationship, computed using a typical cross section and an average slope for the canal. The surface water system that lies within the test area is not a closed system as the excess water that runs along the interdunes located in its north west side discharges into the catchment that drains to the Hinojo-Las Tunas lake. The reservoirs and spill units used in those interdunes discharging to an external sub-catchment were ended with a fixed head time condition to simulate free discharge.

Finally, nominal flows were estimated in order to feed the reservoirs located at the northern and southern limits of the pilot area; these flows simulate inflows from outside the pilot area.

The initial conditions for layer 2 of the TAM were extracted from the RGWM and then resampled at the resolution of the test model, 500m. The groundwater heads use as initial conditions represent a groundwater surface representative of the situation of the aquifer prior to 1970: that is prior to the increase in annual rainfall experienced in the region.

Each of the flood cells in iSIS was set with an initial water level equal to the ground level, to represent the depressions in a dry condition prior to 1970.

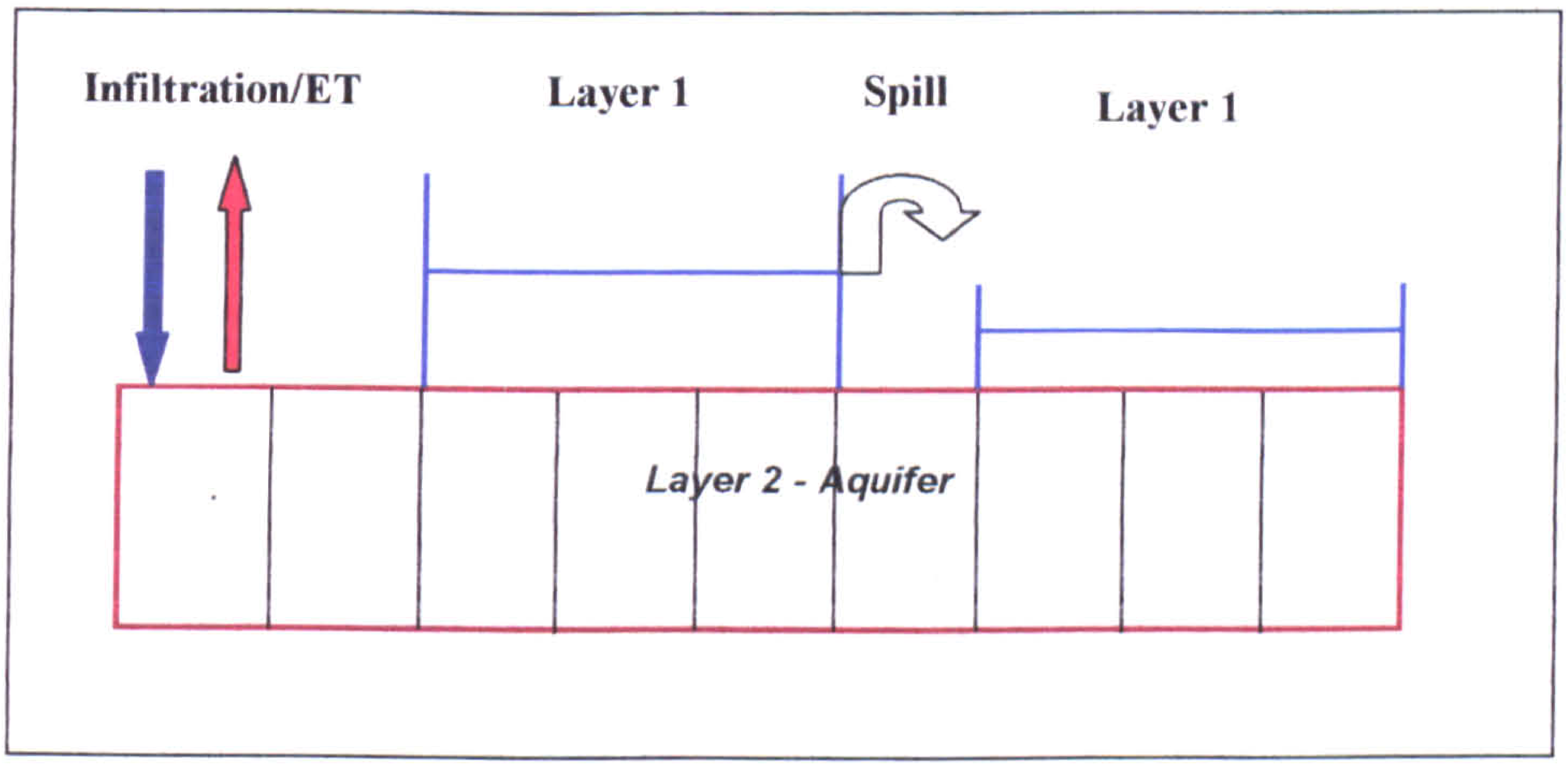


Figure 7.2: Vertical schematisation of test area model.

7.3 Selection of Time Steps to Run iSISMOD

The large difference in time steps usually required to represent the dynamics inherent to groundwater and surface water systems are a recurrent difficulty highlighted in the literature on GW-SW interaction. The physical system of the test area is not an exception and, while the groundwater system requires a monthly time step to reproduce its flow system, the dynamics on the surface would require a daily time step. The daily time step was necessary mainly to take into account the duration and variability of rainfall events. Figure 7.3 presents a typical rainfall event for the test area, where it can be observed that there are large differences between daily and monthly rainfall values. However, a close inspection of the coupled system to analyse operational aspects of a land drainage system, encompassing the operation of hydraulic structures, could imply reducing the order of magnitude of both time steps, ending with an hourly time step for the surface system and a daily one for the groundwater system.

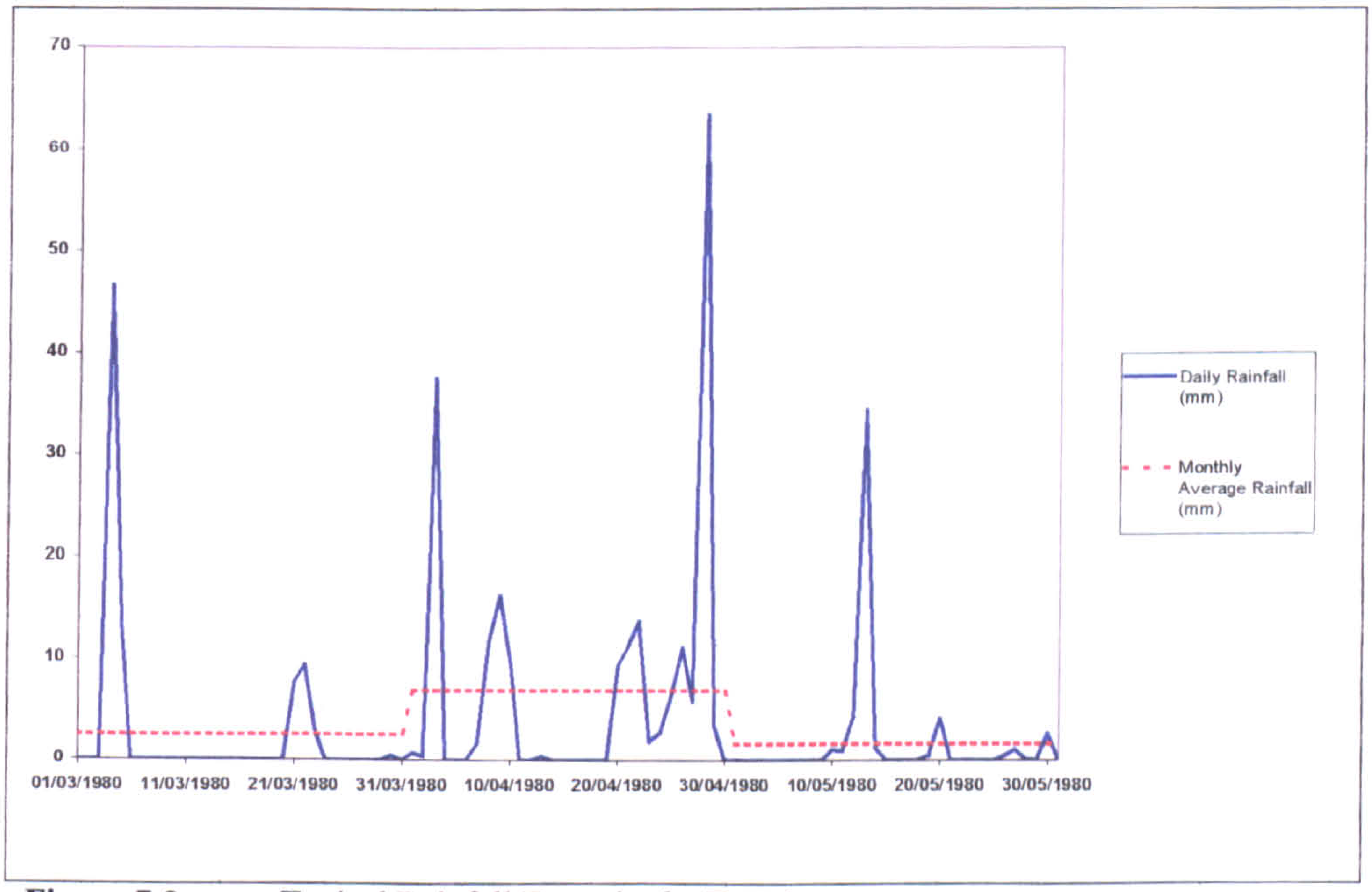


Figure 7.3: Typical Rainfall Event in the Test Area.

Initial runs were carried out with iSISMOD using a monthly time step for Layer 2 and a daily time step for Layer 1. However iSISMOD failed to converge due to large oscillations in groundwater heads, leading in all cases to an erroneous drying out of the aquifer system. This results from the internally decoupled set of equations solved in iSISMOD; this implies that the mass balance equation is solved in each program using leakage-related terms explicitly. Only in the case where both time steps coincide (for layer 1 and 2), could then the continuity equation for groundwater flow be resolved implicitly. Figure 7.4 exemplifies the potential instability issue due to large differences in time steps.

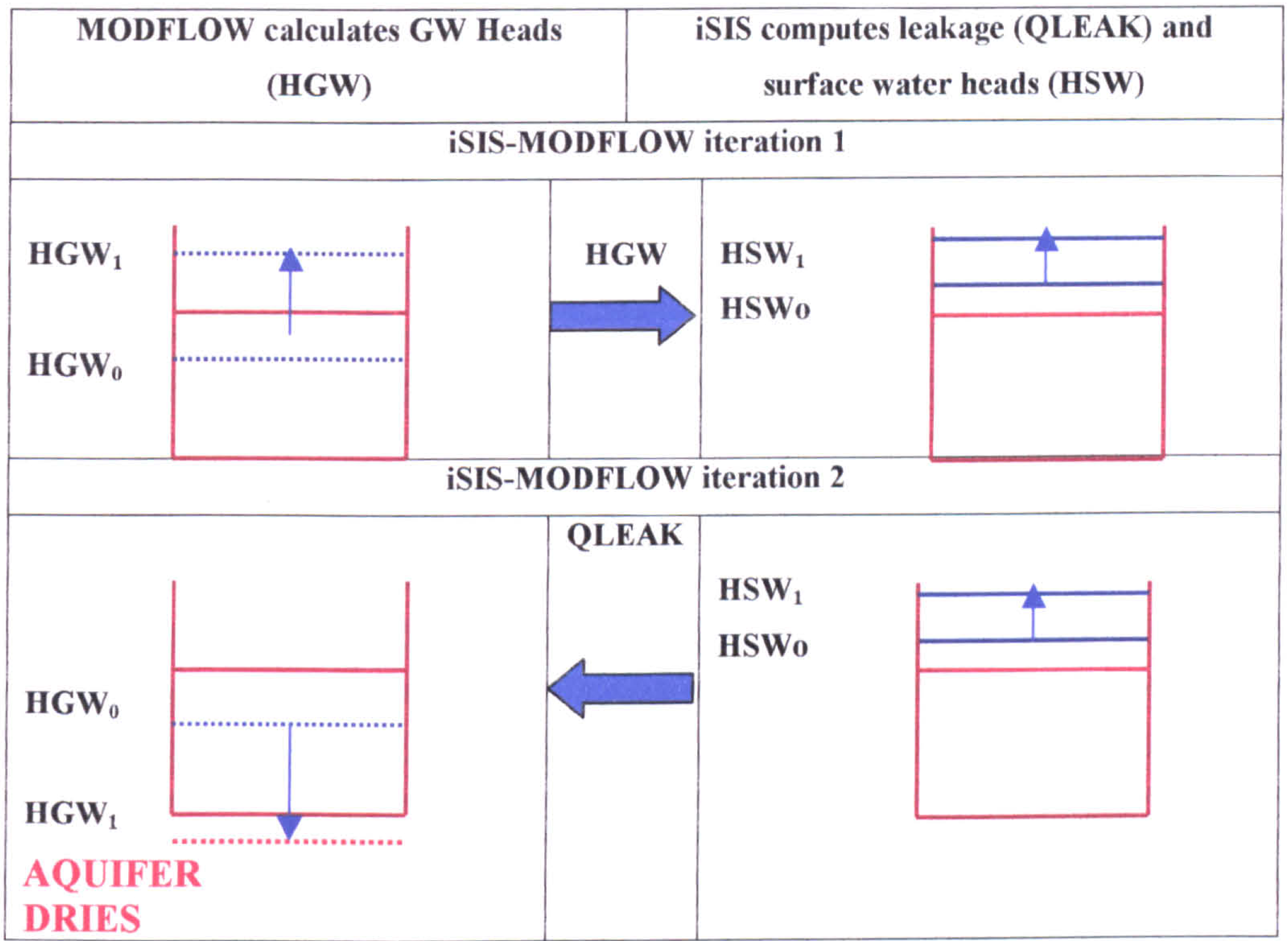


Figure 7.4: Conceptual Representation of Aquifer going dry due to non convergencies between iSIS and MODFLOW.

MODFLOW goes from HGW_0 to HGW_1 over an aquifer time step (say 1 month)
iSIS goes from HSW_0 to HSW_1 over n surface water time steps (for 1 day, n is 30)

Another situation that could lead to non-convergence of an iSISMOD run could arise if there is a change in the sign of leakage during its computation over the iSIS time steps. Figure 7.5 exemplifies this situation.

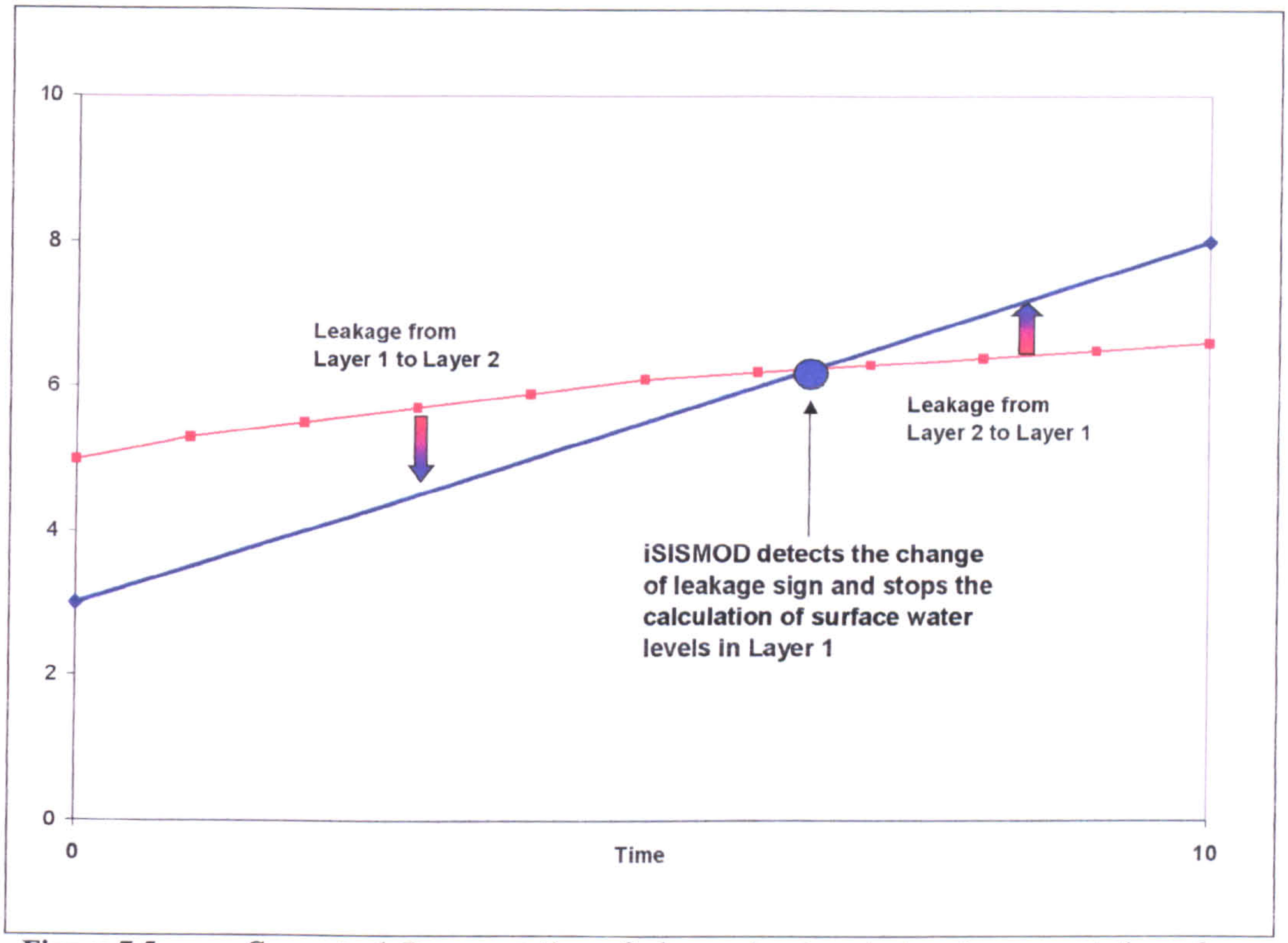


Figure 7.5: Conceptual Representation of change in sign during the computation of leakage by iSIS.

As a result of these problems, iSISMOD was further developed from its original form (Chapter 6) to overcome these limitations. The problem of non-convergence between programs is addressed by :

(i) imposing a maximum physical volume of leakage that can be extracted from the aquifer at any MODFLOW time step. This is calculated as the storage based on the groundwater heads at the beginning and end of a MODFLOW time step. This guarantees that the aquifer head cannot drop below the head at the beginning of the time step (i.e the final head calculated at the end of the previous time step)

(ii) stopping the computation of the cumulative leakage in iSIS when a change in sign is detected due to the surface water level intercepting the interpolated groundwater head.

These two modifications to iSISMOD proved to give significant robustness to the program permitting it to run successfully the simulations described in the following two sections. Therefore, the time steps for running iSISMOD were selected on the basis of the need of each individual system. For iSIS an hourly time step was finally chosen in order to maintain stability of the simulation during functioning of the spill units to transfer water from one cell to another. A larger time step should have been used if more time had been devoted to develop a more discretised surface water model with more flood cells and transfer units so that the flow between cells is smaller.

For MODFLOW, a daily time step was selected in order to use the daily time series of infiltration and rainfall data in the simulations.

7.4 iSISMOD and the Generation of FPMs for the Baseline Situation

The key shortcoming of the approach described in Chapter 5 was its inability to reproduce the mechanisms of conveyance and storage of surface water, once exfiltrated from the underlying aquifer. The first simulations carried out with iSISMOD consisted in running the model for the wet period that took place between 1985 and 1990, in order to compare the prediction of flooding with that observed in the interpretation of satellite imagery. Figures 7.6A and 7.7B resent the same profiles analysed previously in Chapter 5, but with the results obtained using iSISMOD for layers 1 and 2. These figure show how iSISMOD generates a water profile that represents the dynamics of water on the surface, characterized by:

(i) a single water level in coincidence with each depression, and
(ii) a cascading profile, indicating the transfer of water from one depression to the next downstream.

Groundwater heads (layer 2) were also plotted in both figures. A closer inspection of the profile of both layers (Figures 7.6A and 7.6B) leads to identification of three GW-SW areas:

a. areas where groundwater heads are below the ground surface indicating that no exfiltration to the surface occurs,
b. areas where the surface and ground water levels are above ground surface (i.e. in correspondence with a depression) indicating active interaction between both systems, and
c. areas where the groundwater heads are well above ground surface with no indication of a surface water level. This reflects a shortcoming in the schematisation of the model indicating that this area should have been represented in layer 1 to capture the dynamics of the exfiltrated water.

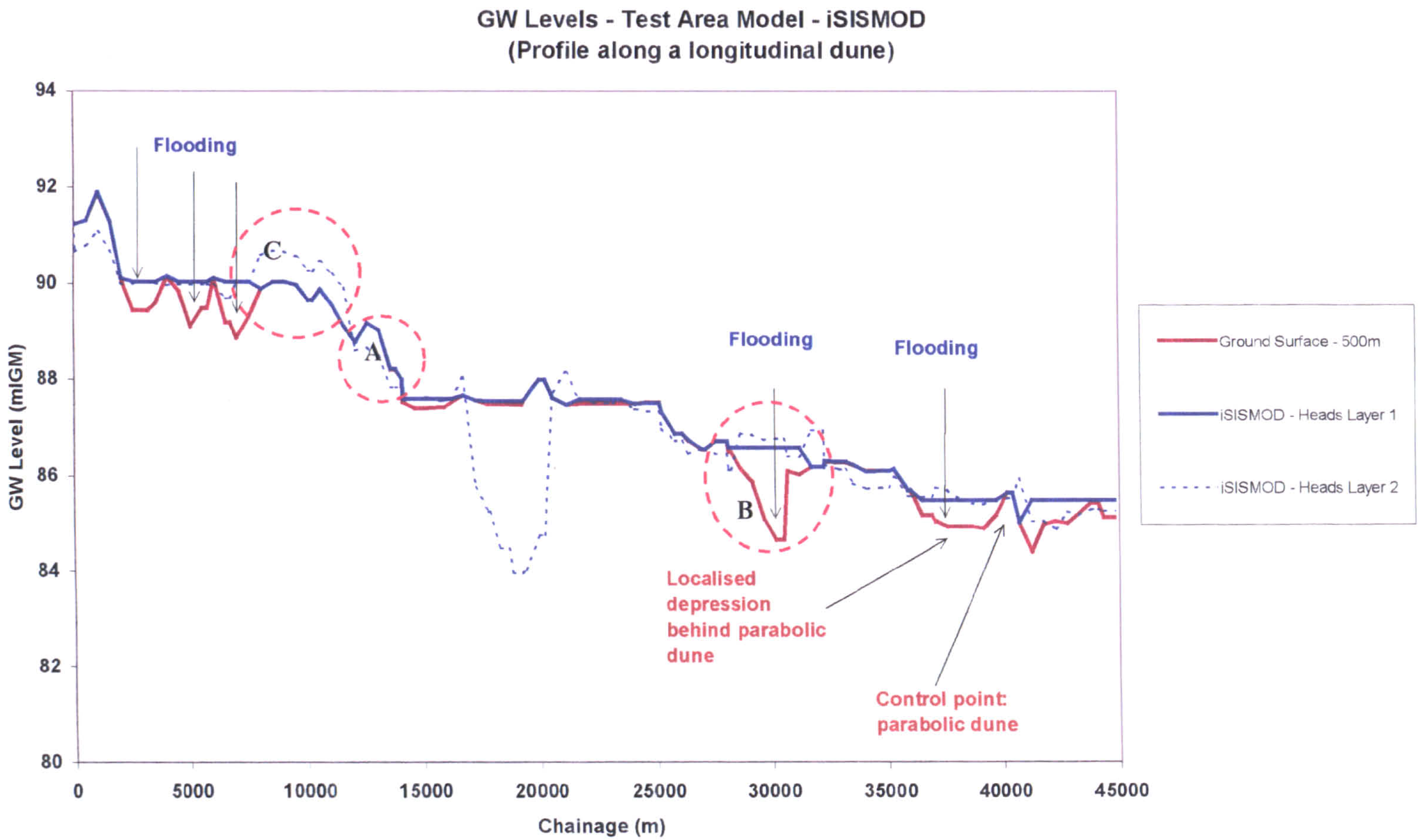


Figure 7.6A: Test Area Model – iSISMOD – Surface and groundwater profiles. Profile 1. Daily infiltration time series.

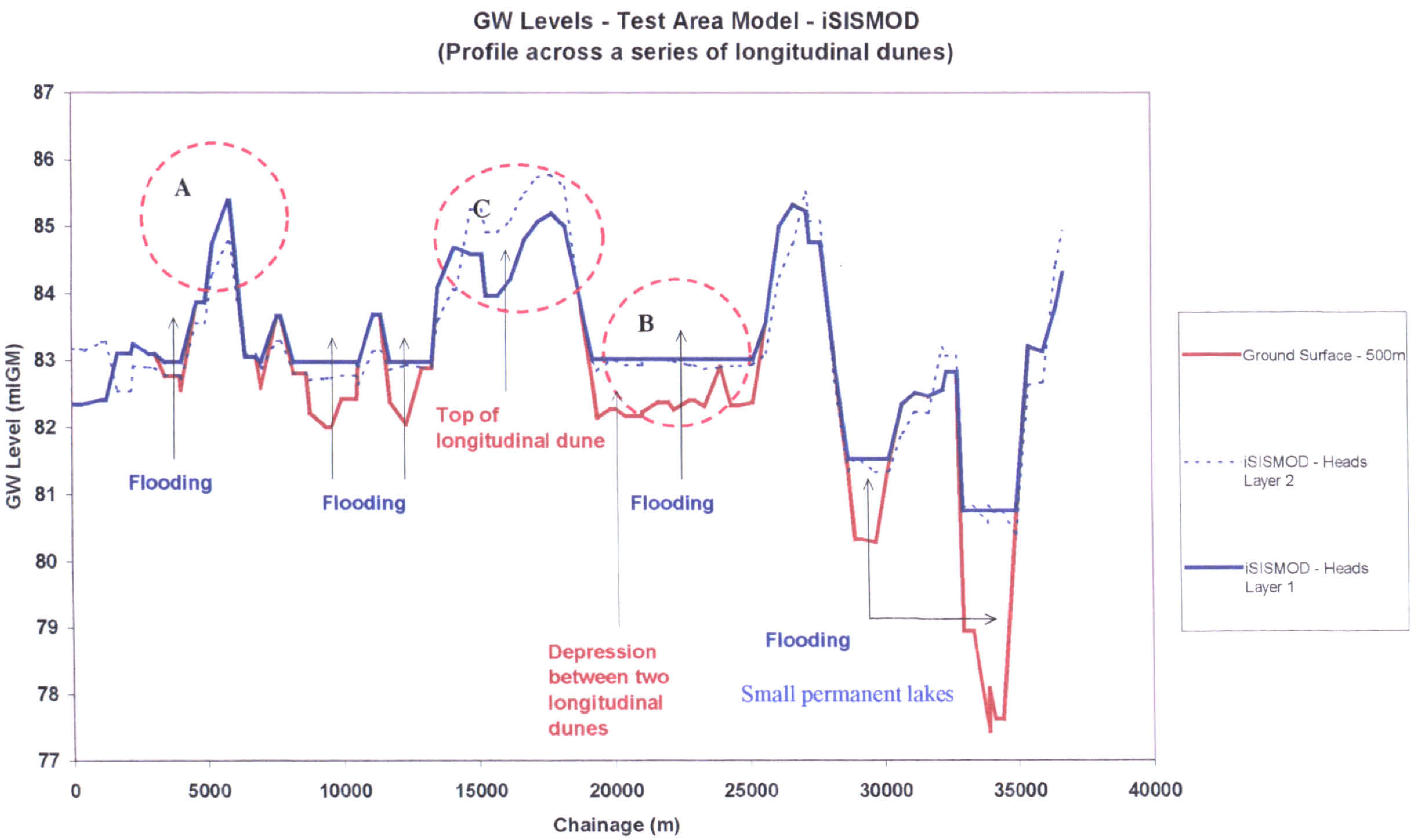


Figure 7.6B: Test Area Model – iSISMOD – Surface and groundwater profiles. Profile 2. Daily infiltration time series.

These three configurations are indicated in Figures 7.7A and 7.7B.

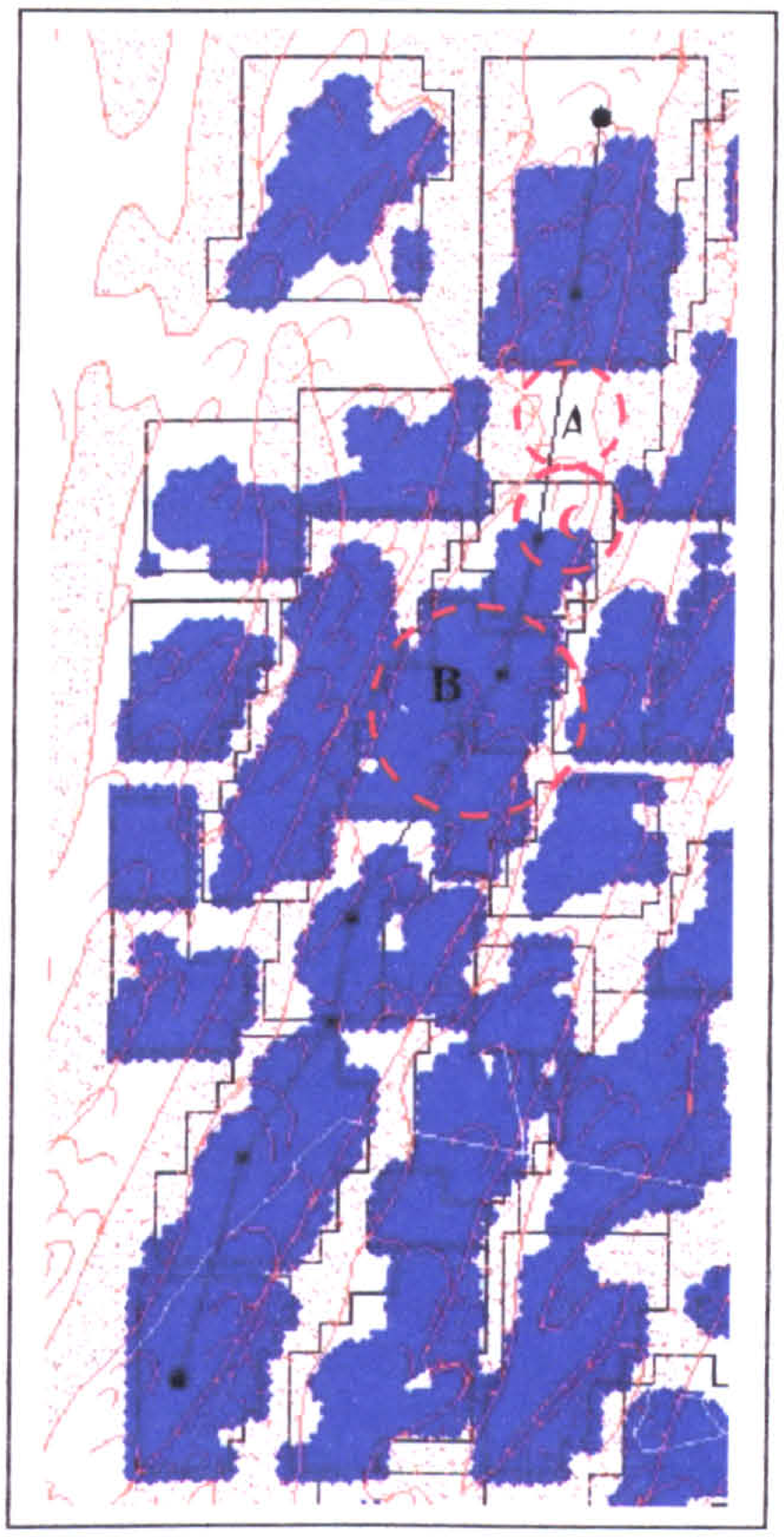


Figure 7.7A: Plan view of flooded areas. Profile 1.
Test Area Model – iSISMOD – Daily infiltration time series.

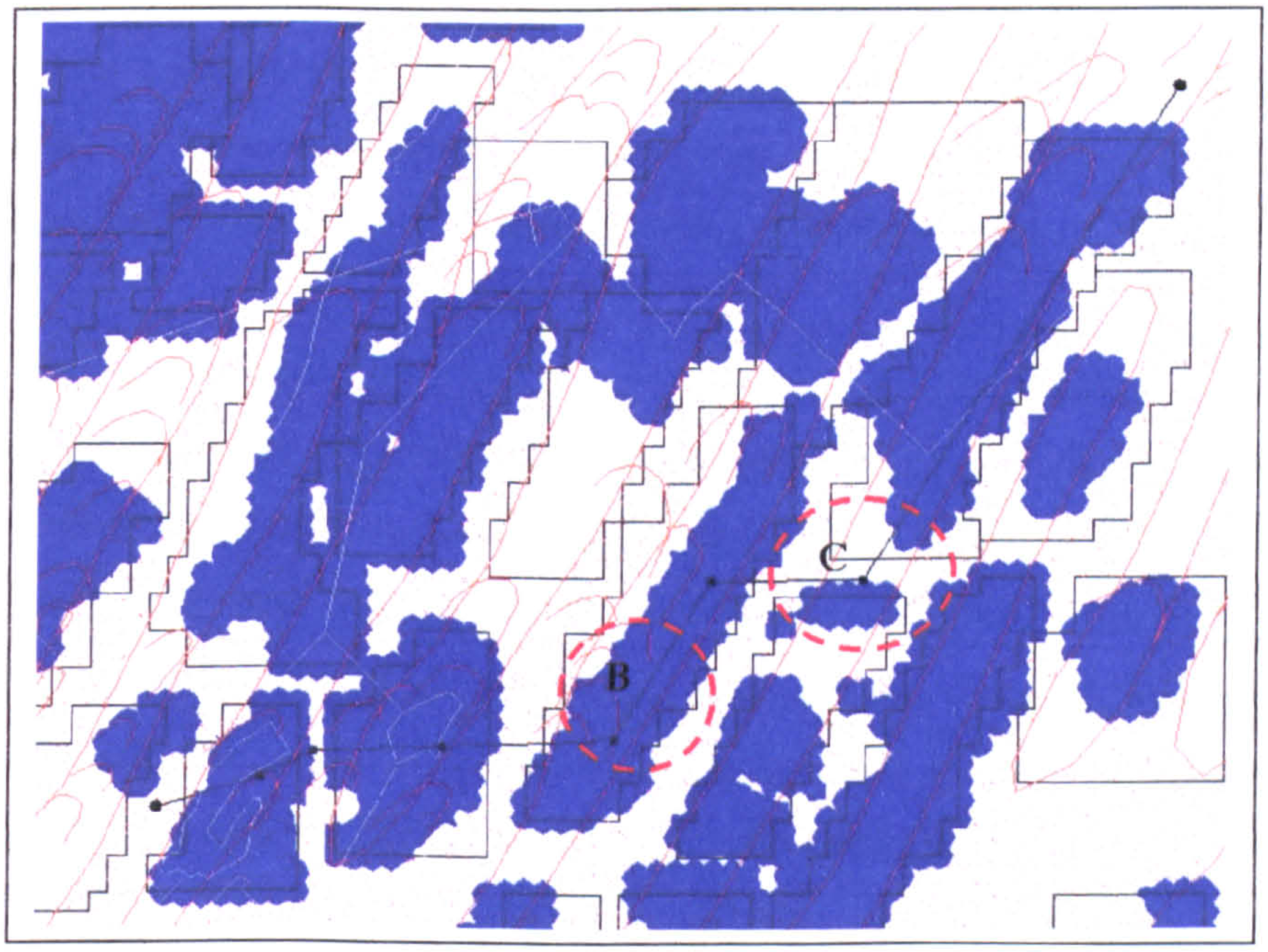


Figure 7.7B: Plan view of flooded areas. Profile 2.
Test Area Model – iSISMOD – Daily infiltration time series.

Level hydrographs for layers 1 and 2 are presented in Figure 7.8. These locations were selected to characterise in more detail interaction between layers 1 and 2, in one of the areas classified as B along profile 1. The hydrograph for observation point 4, located in the deepest part of the flood cell, has a groundwater head higher than the surface water level indicating an area of leakage from the aquifer to the ground surface. For the rest of the observation points, the opposite mechanism takes place. Differential heads between both layers are small as it would be expected from the large vertical conductivity value set for the interface, 1m/day.

The anomalies (such as those classified as C above) suggests the need to schematise the model iteratively. This means to increase the number of flood cells in layer 1 as more areas subject to exfiltration are identified in preliminary runs. The initial schematisation of the model could be initially carried out using a DEM and a geomorphic map to identify likely areas subject to flooding; the availability of satellite imagery would also be very important to detect historically flooded areas. This was basically the process followed for the development of the TAM model. The initial runs would permit to identify the locations of areas for which the groundwater head emerges to the surface, dictating that layer 1 of the model should be extended to cover those areas too. Re-schematisation could also encompass further discretisation of existing flood cells, in those areas where ponding takes place over large areas and therefore there might be a need to account for the slope of the surface water profile.

The next stage in the analysis centres on the adequacy of iSISMOD in reproducing the dynamics of water once it arrives at the surface and comparison of the flood extent in the model and comparison of the flood extent in the model with that interpreted from satellite images, as presented in Chapter 5. Figure 7.9 shows the maximum flood extent obtained with iSISMOD, indicating that a better representation is obtained in comparison with to the maps generated in Chapter 5. However, the results from iSISMOD still fail to depict the connectivity of surface flooding and a real extent revealed by the satellite imagery. This could be a consequence of not having the right volume of water emerging to the surface: if so, would initially suggest that the rainfall-runoff model HYSIM overestimates the surface runoff component of the terrestrial water cycle and, therefore, underestimates the amount of infiltration. Chapter 3 presented a water balance from HYSIM for the test area indicating that runoff is less than 5% of rainfall, net of interception storage and evaporation from open surfaces. However, the complete absence of a natural surface water drainage network could justify not having any initial surface runoff at all in the area. But also, an underlying problem in the use of HYSIM is that it cannot handle any of the dynamics of the hydrological process that take place in the area related to infiltration, evaporation from open surfaces and runoff.

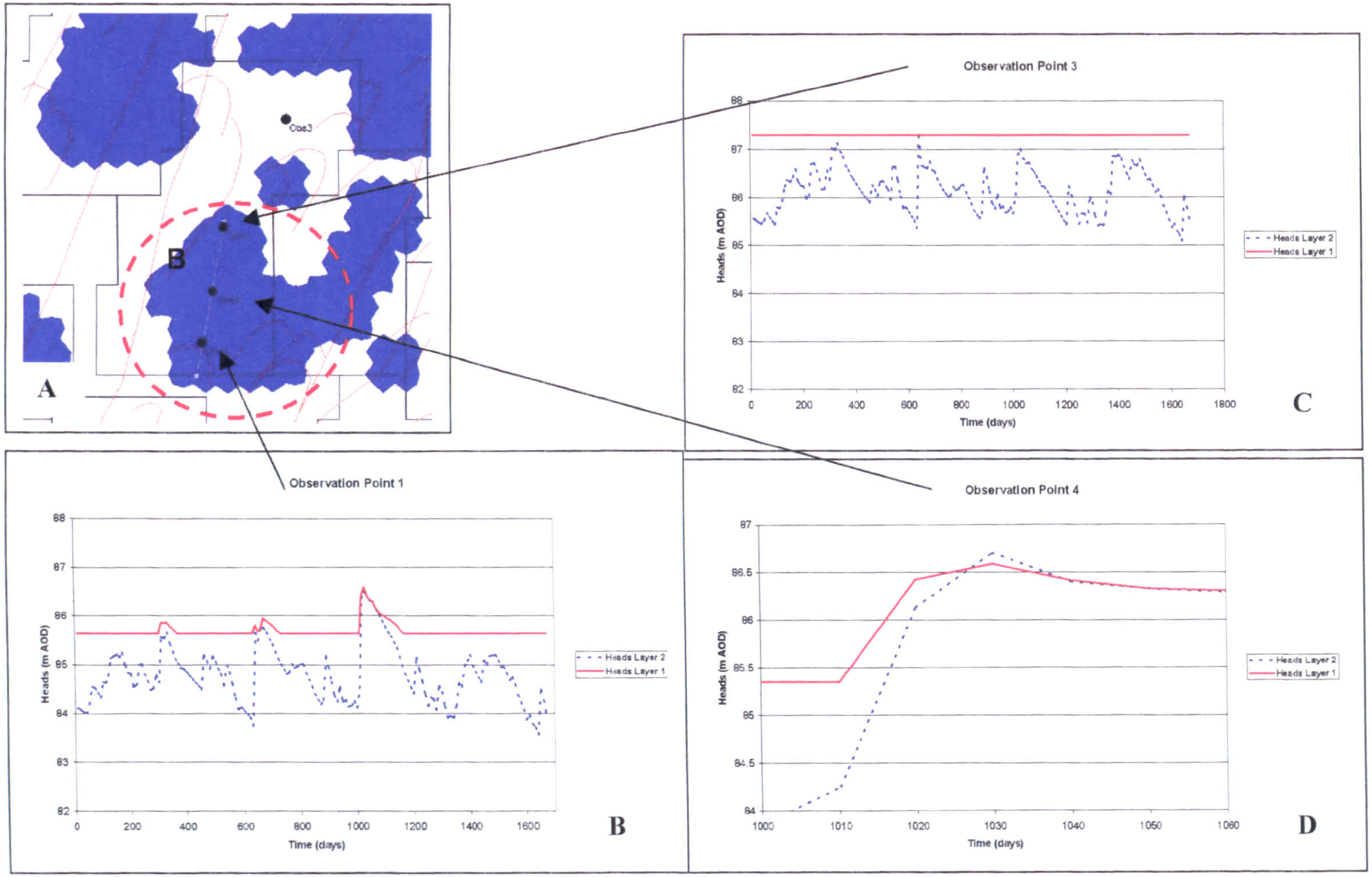


Figure 7.8: **A**. Location of layer 1 and 2 level hydrographs. **B**: observation point 1, inside flooded area. **C**: observation point 3, outside flooded area. **D**: observation point 4, deepest point in flooded area, levels shown for the period where the peak surface water level occurs.

In order to test the sensitivity of flood extent to an increase in the amount of water entering the aquifer, a simulation was carried out using daily rainfall instead of daily infiltration. The resulting flood extents are shown in Figure 7.10.

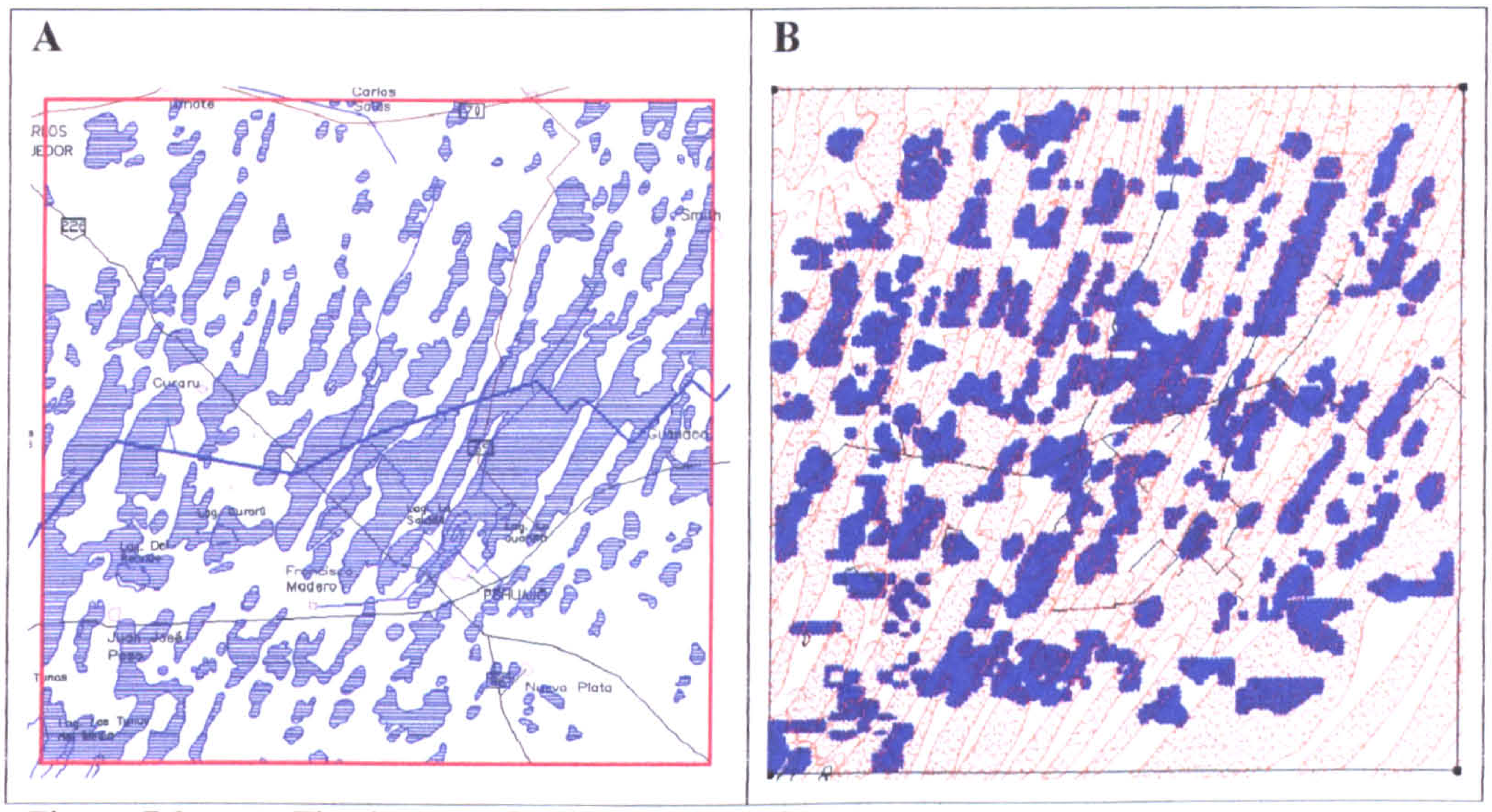


Figure 7.9: Flood extents for the March 1988.
A: flooding from satellite image.
B: flooding predicted by iSISMOD (run 3).

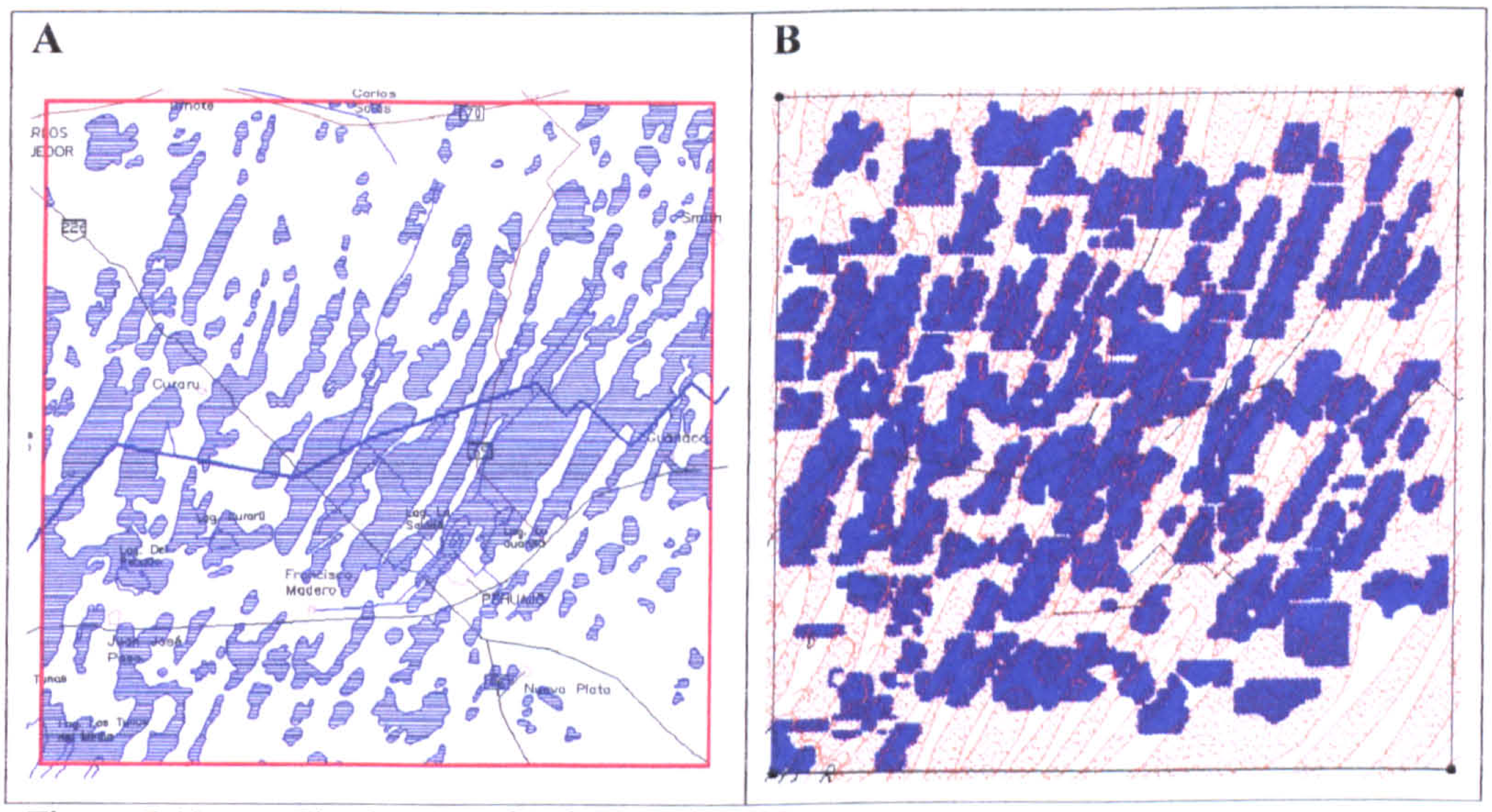


Figure 7.10: Flood extents for the March 1988.
A: flooding from satellite image.
B: flooding predicted by iSISMOD (run 6).

This approach shows that, effectively, the flood extent increased as a result of using rainfall in place of infiltration and that the connectivity of flooding evident at the surface in the satellite imagery begins to be reproduced in the model (Figure 7.11).

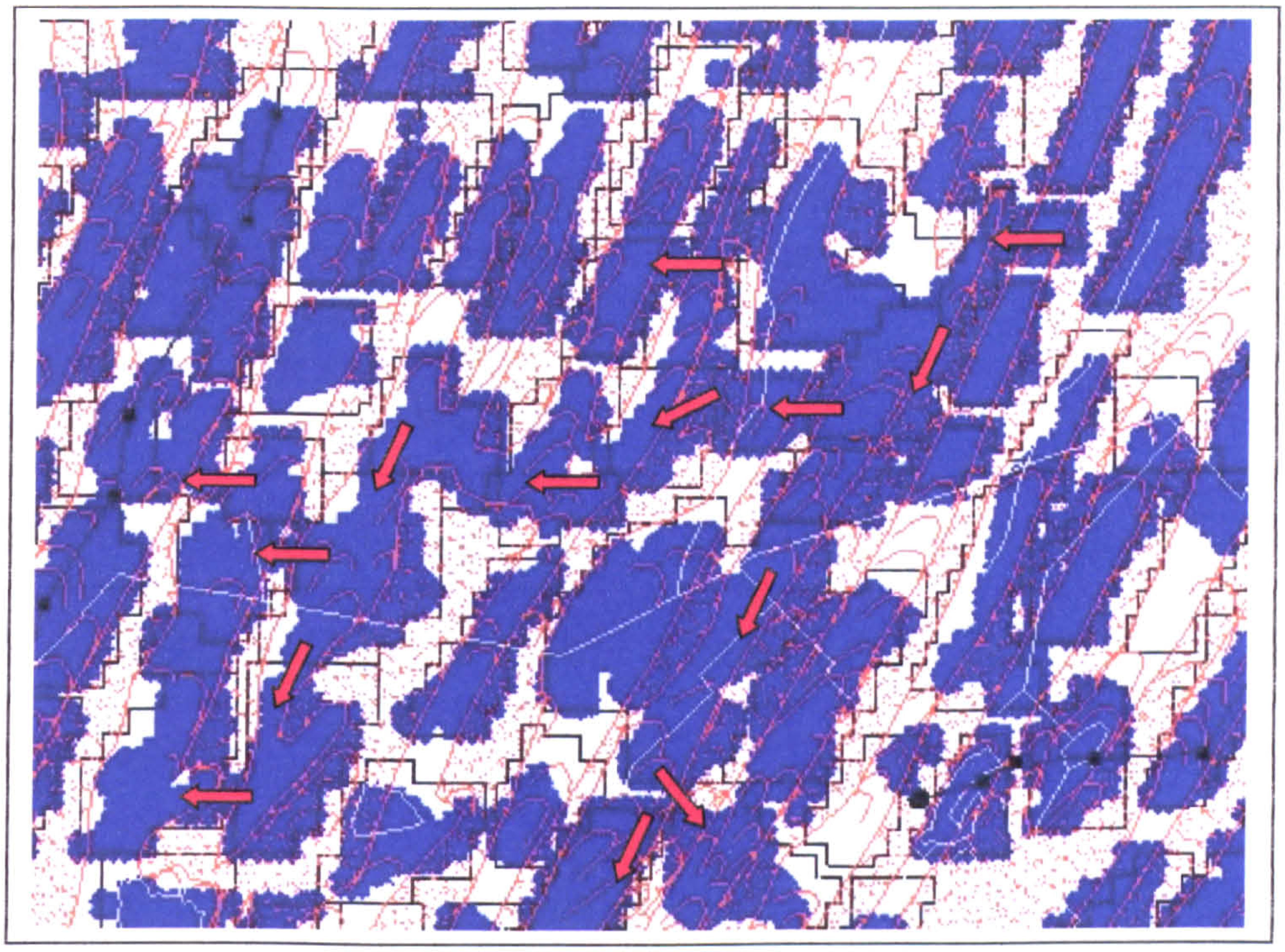


Figure 7.11: Connectivity of surface flooding.

This further suggests the need to include within iSISMOD some representation of direct rainfall and evaporation from saturated surfaces on the ground. Figure 7.12 shows a conceptual schematisation of the proposed functioning of this new feature of the program (in addition to what has been described in Chapter 6), which would perform the following calculations:

(i) iSISMOD detects where there is a *Flooding* or *No Flooding* situation, depending on whether the water level in layer 1 is above or below the ground surface. This check is performed for every surface water time step and for every cell of the model.

(ii) For those cells where a *flooding* situation is detected, MODFLOW does not include infiltration in the continuity equation for layer 2 but only the leakage originating from layer 1. At the same time, the continuity equation for layer 1 will include a rainfall and an evaporation term.

(iii) For those cells where a *no flooding* situation is detected, MODFLOW will take the infiltration or recharge term from a hydrological model.

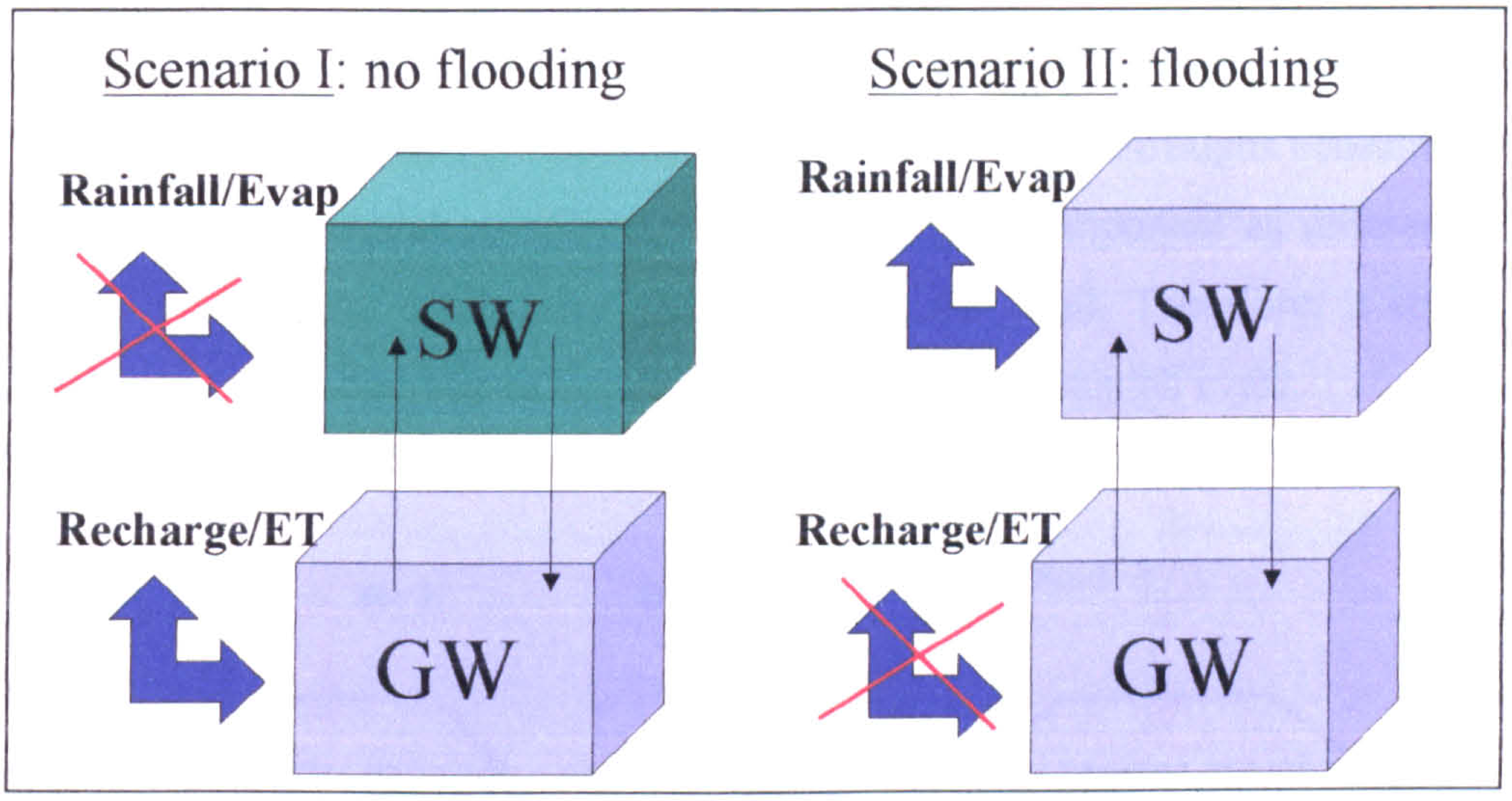


Figure 7.12: Representation of the simulation of saturated overland flow in iSISMOD.

Although the results from iSISMOD presented above proved to be heading in the right direction to be able to predict the extent of groundwater-induced surface flooding, examination of a sequence of flood maps for a real flood event (such as the one in 1987/1988) indicates that the model simulates exfiltration and infiltration processes faster than is observed. This could be overcome by varying the vertical conductivity spatially. The results presented above used a constant vertical conductivity value of 1m/d for the entire test area; but as was mentioned earlier in the chapter, low permeability soil horizons are found in coincidence with interdunal depressions and therefore, a lower value of vertical conductivity could be justified in these locations. This would imply higher differential heads between layer 1 and layer 2 and a longer period with exfiltrated water standing on the surface. A reduction of vertical conductivity, combined with the approach presented in Figure 7.12, would result in a closer representation of the different dynamics of infiltration and exfiltration processes that take place in the high and low parts of the dune field.

Figure 7.13 conceptualises this issue. Basically, the exfiltration process is characterised by a fairly rapid infiltration of water through the top of the dunes due to the high infiltrability of sandy soils and a rise in groundwater levels is followed by leakage to the low depression areas. Leakage through the low permeability soil layer located underneath each depression also takes place, but at a slower rate. As water emerges in the depressions, flooding increases at a faster rate due to the impact of direct rainfall falling onto the saturated areas. Reversal of this process, termed re-infiltration, occurs at a much slower rate due to the low vertical permeability of the soils in the dune troughs beneath the flooded areas. Lateral re-infiltration is not a major component as differential heads between the depressions and the dunes are small. Therefore, it seems logical to expect flooding to last for several days after a rainfall event.

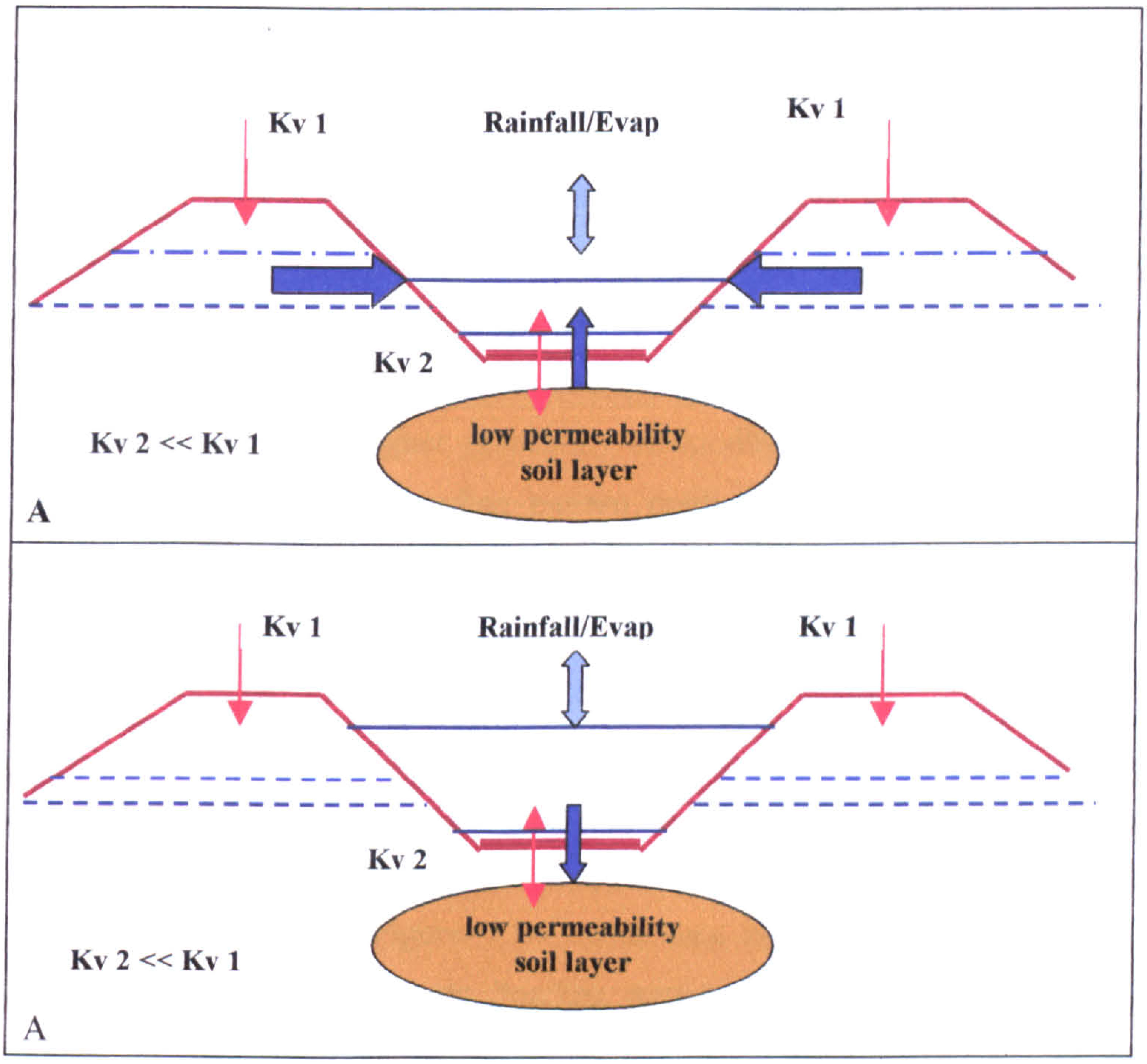


Figure 7.13: Representation of the dynamics of exfiltration and infiltration under varying soil conditions. A: exfiltration. B: reinfiltration.

The usefulness of iSISMOD has been investigated in relation to the generation of water levels at the surface, the downward transfer of water controlled by micro-relief features (crest elevation of parabolic dunes) and reproduction of the dynamics of flooding through the exfiltration and re-infiltration processes. The final step is to analyse whether the results obtained using iSISMOD improve the generation of FPMs. The time series of surface water levels predicted by the model using an infiltration and daily rainfall time series were selected to generate new FPMs. Figure 7.14 allows direct comparison of the FPMs obtained using iSISMOD, with those obtained using MODFLOW alone.

Application of MODFLOW to produce a FPM for the test area, with a grid size of 5000m (as used in the regional approach adopted in the IMP studies (Chapter 5)) produces a poor representation of flood probability in the test area (Figure 7.14A). The FPM under predicts flooding in both extent and frequency, which is to be expected given the very coarse representation provided by the 5000m grid and the inability of the model to reproduce the dynamics of water in the surface. Using a finer resolution (500m) improves the identification of areas subject to groundwater-induced flooding and that is reflected in the FPM shown in Figure 7.14 (B), which shows a larger area subject to events of all return periods. In this FPM, areas with return periods of surface flooding between 2 and 5 years are fairly uniformly distributed throughout the area, with a pattern of areas with higher probability of flooding inside areas with lower probabilities. The overall flooding pattern predicted in the test area simply reflects that identification of flooding/no flooding situations is made purely on the basis of a vertical balance, expressed by the rising of groundwater heads to the ground surface.

The FPMs obtained with iSISMOD overcome many of the limitations described above for the MODFLOW approach. The first FPM (using daily infiltration) is shown in Figure 7.14C This map is an improvement in that larger areas with more frequent flooding start to appear in the downstream parts of the test area, even though the overall extent of flooding decreases in comparison with the FPM obtained using MODFLOW for a 500m resolution. This is a consequence of two issues: the first is inherent to the functioning of both the flooding system and the model in the sense that water exfiltrated from the aquifer initially collects in the lowest point of the interdunal depressions and then flooding progressively increases according to the stage/area relationship of each micro-relief feature. It follows that it is indeed correct not to have a flooding pattern that followed too closely the relief pattern. The FPM with iSISMOD was carried out using the heads from layer 1 and iSIS to convert those heads into overland flow; if the heads from layer 2 had been used, the results would have been more similar to those obtained in the previously reported FPM with MODFLOW and the 500m resolution. The second issue that conditions the extent of flooding is the schematisation of layer 1 and the coverage of the surface areas with flood cells. The resulting FPM will only show a probability of flooding in those areas covered by flood cells. This second issue could be overcome if the interdunal depressions are simulated in iSIS using river units capable of predicting a surface water level along the entire reach of the depression, avoiding the gaps left by the schematisation using reservoirs and spill units.

Finally, the FPM obtained using daily rainfall instead of daily infiltration (Figure 7.14D) provides the opportunity to observe a number of features:

(i) the predicted flooding has increased throughout the area in extent and frequency; in particular it is noticeable the extent of areas flooded with a 2years return period. It is expected that the use of iSISMOD with a larger stress (such as rainfall as opposed to infiltration) generates a larger flood extent. However the appearance of numerous upstream areas frequently flooded is, at least, doubtful as this is likely to be more related to an exaggeration of one of the vertical components of the water.

(ii) a change in the frequency of flooding in some downstream areas (previously depicted by the other approaches) is the logical consequence of areas now receiving more water coming from upstream areas. However, it is not possible by the mere examination of this FPM to distinguish between this and the first aspect.

(iii) the appearance of downstream areas (not previously depicted by the other approaches) subject to flooding for events of low probability of occurrence is also an expected feature emerging from the use of iSISMOD that can simulate when water exceeds the threshold of the micro-relief.

(iv) In theory, if the water balance is simulated correctly, then the frequency of flooding of upstream areas (those that initiate the induced flooding situation, i.e. runoff initiation areas) should not change. The fact that this does occurs emphasises what was expressed in point (i).

The approach to producing FPMs based on application of iSISMOD seems to be the way forward for the generation of more realistic, physically-based predictions, although limitations inherent to the basis of the FPM methodology mask some of the advantages over using MODFLOW alone. Specifically, the fact that the maps are based on calculation of the annual probability of the occurrence of flooding means that the FPMs are rather insensitive to the approach adopted. This was one of their strengths in terms of the studies used to support the IMP for the Rio Salado basin as it made the results extremely robust. However, the annual basis for flood probabilities is not the right vehicle for realising the benefits of more physically-based, coupled models of flooding processes in the generation of flood probability maps. The benefits of improved modelling could, however, be carried through to flood prediction and management if the annual series for flood probability analysis were replaced by a peak-over-threshold analysis based on records of each flood occurrence.

iSISMOD delivers better insights into the likely impacts of flooding by supporting estimation of the velocity, depth and duration of flooding due to different events. Potentially, this could be used to generate bi-variate FPMs to show the frequency of occurrence of flooding events of different magnitudes, quantifying this through representation of both the duration and depth of flooding. Furthermore, this would support broader and more informative agro-economic analyses, with the possibility of assigning different economic damage to each agricultural and livestock enterprise depending on the types and physical thresholds of flooding that affect each of them.

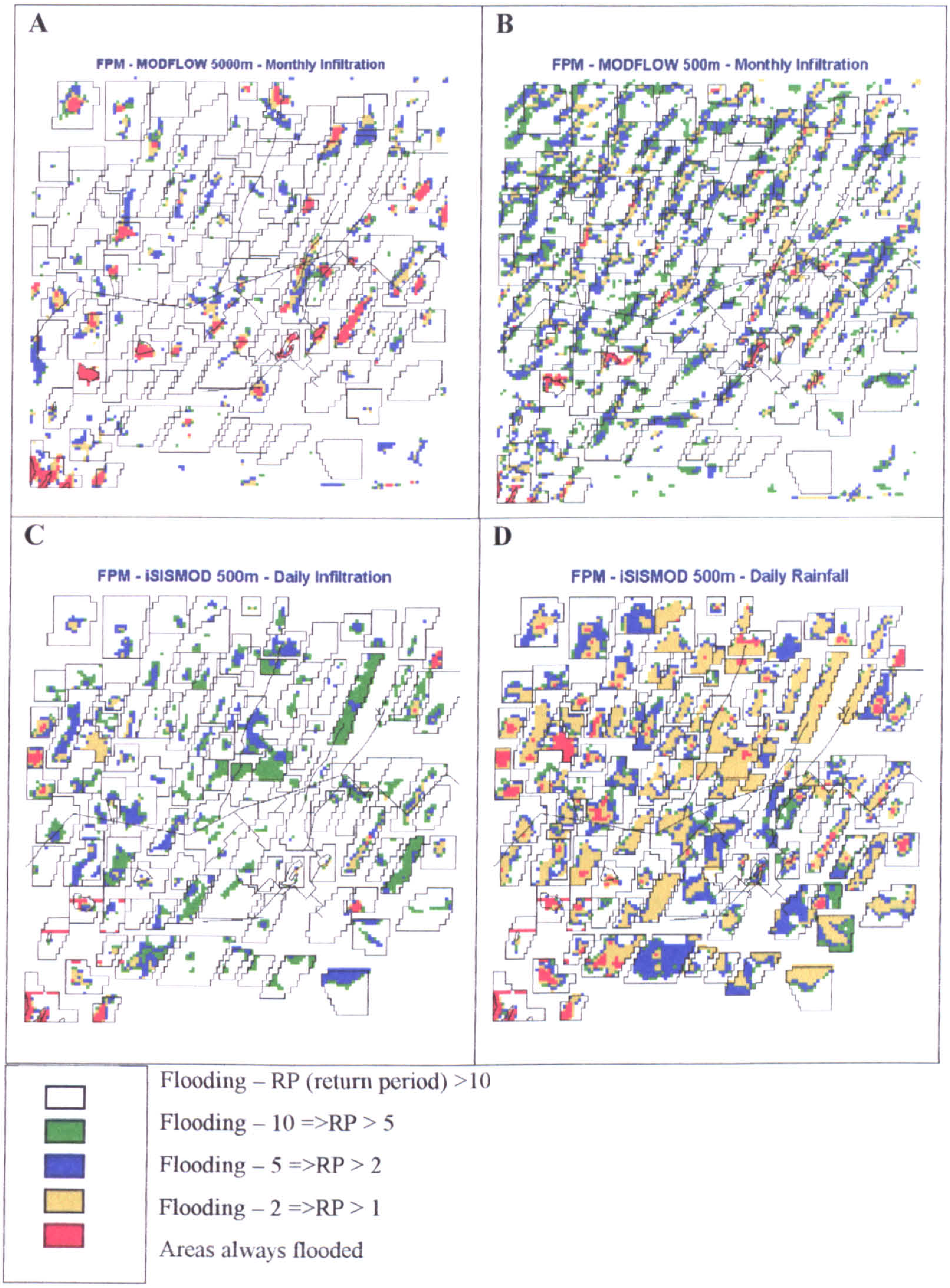


Figure 7.14: Flood Probability Maps.

A: MODFLOW – 5000m – Monthly infiltration.

B: MODFLOW – 500m – Monthly infiltration.

C: iSISMOD – 500m – Daily infiltration.

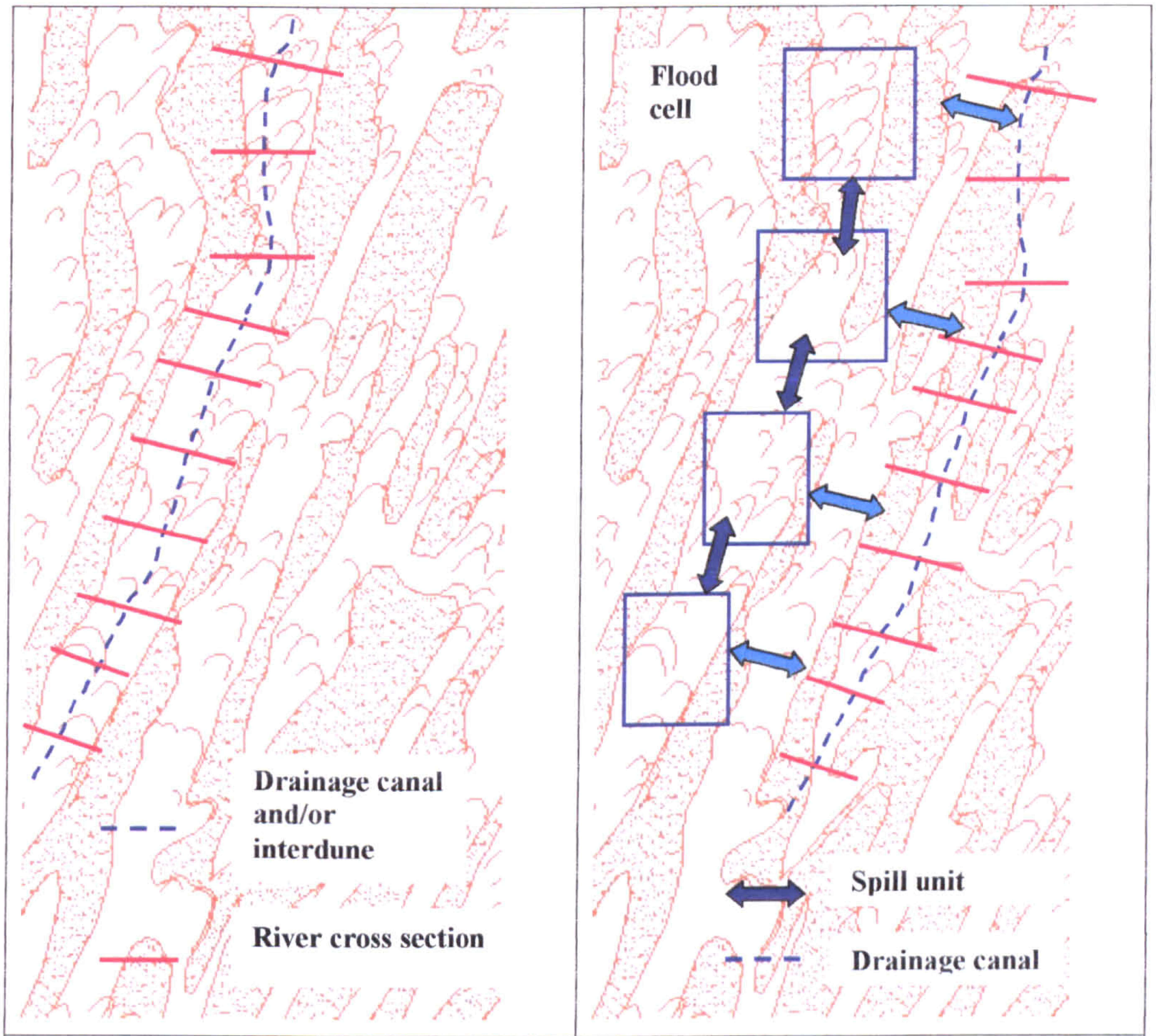
D: iSISMOD – 500m – Daily rainfall.

7.5 iSISMOD and Generation of FPMs for the Project Scenario

Chapter 3 explained the need for a dense network drainage of channels to manage the groundwater-induced surface flooding and waterlogging in the Northwest, including the test area. Chapter 4 presented the concept of drainage rates and the use of modelling approaches for their estimation. Chapter 5 exemplified how MODFLOW was used in the IMP to estimate the impact of the implementation of a drainage system providing a level of service of 10-years, through an implicit approach that consisted of modification of the infiltration time series that was entered into the groundwater model. However, the canals that would be constructed to provide drainage were not included explicitly in the schematisation of the model. This section outlines the potential application of iSISMOD to estimate drainage rates and their impact in the northwest region, analysing the strengths and weaknesses of the approach.

The main weakness of the approach presented in Chapter 5 was that the performance of the canals was prescribed, based on a conceptual understanding of their functioning and, therefore, the assumptions implicit to their predicted performance were then translated into the generation of the "with project" FPM. For example, in the generation of the final FPM used to estimate the areas benefiting from the drainage schemes, it was assumed that all surface drainage would be conveyed satisfactorily by the design section of the canals. In fact, using MODFLOW alone cannot provide a better alternative to dealing with this situation in light of the weaknesses demonstrated in this research with respect to simulating surface processes. Conversely, as was explained in previous sections, iSISMOD does provide the necessary simulation options to represent water levels on the surface and, hence the correct driving heads required to estimate the flows entering and moving along a surface water drainage system.

Modelling a drainage system with iSISMOD could be carried out using any of the three different approaches. The first approach (A) would consist of lowering the spill levels that connect the flood cells used in layer 1. This would represent the increase of conveyance that could be gained by cutting across the crest of the parabolic dunes to improve flow along the interdunal depressions. The second approach (B) would consist of replacing the flood cells by river sections extended either side of the axis of the interdunal depression to reach the edge of the longitudinal dunes. If this approach were adopted, to maintain consistency throughout the modelling strategy, the same approach should also be used to generate FPMs for the baseline situation. The third approach (C) would consist of using flood cells linked (via another set of spill units) to a network of drainage canals represented as channels in iSIS. Figure 7.15 presents a schematic representation of approaches B and C.



Approach B	Approach C
Interdunes and drainage canals modelled using river sections.	Interdunes modelled as flood cells and canals modelled as river sections.

Figure 7.15: Modelling drainage canals with iSISMOD. Approaches B and C.

Approach A is the simplest as it does not require any modification to the schematisation of the model other than modifying the spill level to coincide, approximately, with the bed of the drainage canal at that point (approximately 1/1.5m below ground level). However, leaving the existing flood cells in the model implies that an accurate representation of the canal profile would not be achieved. Approach B would be the more appropriate in terms of representation of the drainage canals as it is the only approach suitable to analyse the functioning of the drainage canals not only during a flood event, but also during a normal flow period. This is potentially a major advantage as during non-flood periods the canal would be drawing water from the aquifer, at the potential risk of lowering groundwater levels and damaging agricultural and wetland areas. Approach C is an intermediate approach in terms of the effort required to adapt the model to a project case and in terms of simulation (convergence) complexity. However, Approach C also implies a compromise in the level of approximation to the representation of the functioning of the drainage canals, in particular during a non-flood periods. Figure 7.16 builds on Figure 7.15 to present a more detailed representation of this type of model.

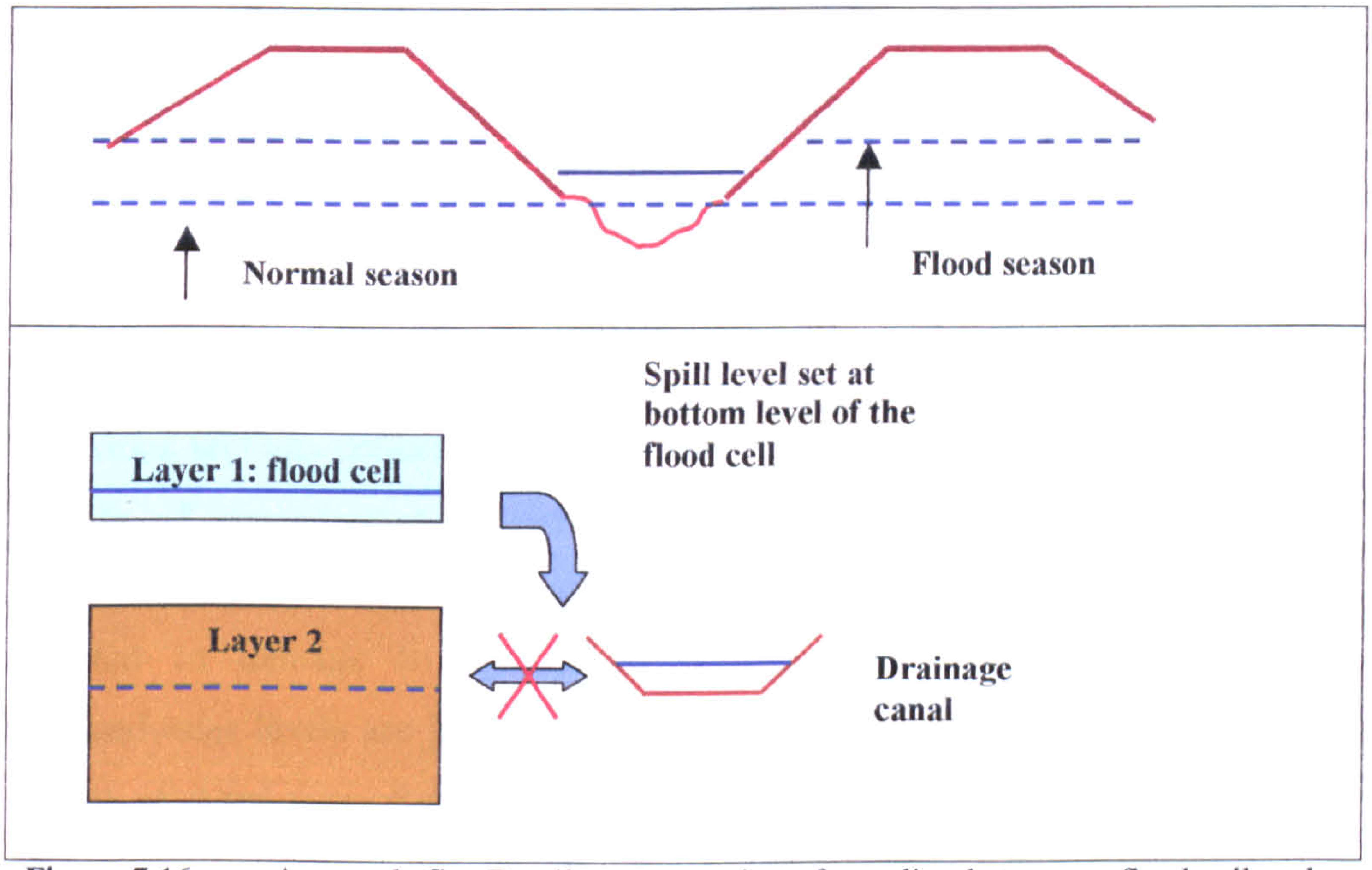


Figure 7.16: Approach C – Detail representation of coupling between a flood cell and a drainage canal.

In Approach C, during a flood event, exfiltrated water from layer 2 arriving in a flood cell would be instantaneously transferred to the drainage canal until its conveyance capacity is satisfied. Water in excess of the conveyance capacity of the drainage canal would be retained in the flood cell as it would in the real situation, as the canal will be designed to convey an average flood flow rather than for the instantaneous peak flow. However, during a non-flood periods, the canal would draw water from the aquifer and this process would not be represented as the only connection between the drainage canal and the aquifer is through a flood cell that would be dry. This problem could be partially overcome if the bottom of the flood cell is lowered below the ground level to match the invert level of the drainage canal, but this would then compromise the solution for the baseline situation, yielding higher frequency of flooding for the low parts of the depressions. In practice, as these areas are of marginal economic value due to poor soil conditions (due to recurrent flooding) Approach C might still be a feasible approximation, however.

In conclusion, the above discussion reveals that iSISMOD is a suitable tool to simulate the GW-SW interaction with the drainage canals in place, and shows that estimation of drainage rates could be carried out by integrating time-averaging through the time series of discharges at the discharge point of each drainage canal, using any one of the three schematics of the surface water drainage system.

7.6 iSISMOD and Waterlogging

Previous sections concentrated in the analysis of iSISMOD for development of FPMs of groundwater-induced surface flooding. Chapter 3 described that waterlogging was also a severe constraint to development as it was more related to damage to agricultural activities. Waterlogging occurs when groundwater levels are just below the ground surface; for example a threshold value of 0.5m was used in the IMP studies to identify these situations. The initial occurrence of waterlogging is due to groundwater levels rising as a consequence of an increase in infiltration (hence recharge).

MODFLOW alone and iSISMOD are equally capable of predicting these situations and the accuracy of their predictions will be primarily related to an adequate simulation of the groundwater profile. With the strong predominance of a vertical balance, the groundwater profile follows the ground profile very closely; therefore, for the Northwest region, the representation of the groundwater profile accurately translates into the need to represent correctly the micro relief features of the terrain. Then, in modelling terms, an increase in the resolution of the model will favour the correct identification of waterlogged areas.

However, there are certain situations for which MODFLOW alone would not be an adequate tool and iSISMOD could provide a better answer. For example, for events in which transfers of water at the surface occur, some areas, not initially waterlogged, can become waterlogged when fed with floodwater from surrounding areas. This should not be an extended feature though as, in general, waterlogging would start from the lower downstream areas, subsequently progressing to upstream areas at upper elevations.

Also, surface water heads would exert some control on the surrounding groundwater levels and, therefore, a correct prediction of the depths of water on the surface –using iSISMOD- could improve the spatial distribution and extent of waterlogged areas. Two situations could occur (Figure 7.17): one is related to waterlogged areas that extent into a fringe zone that surrounds flooded areas and another is related to waterlogged areas generated by flow from flooded areas to the aquifer. However surface water levels should cause a minor impact in groundwater levels as surface water depths are small and should not impose a significant load to the heads in the underlying saturated media.

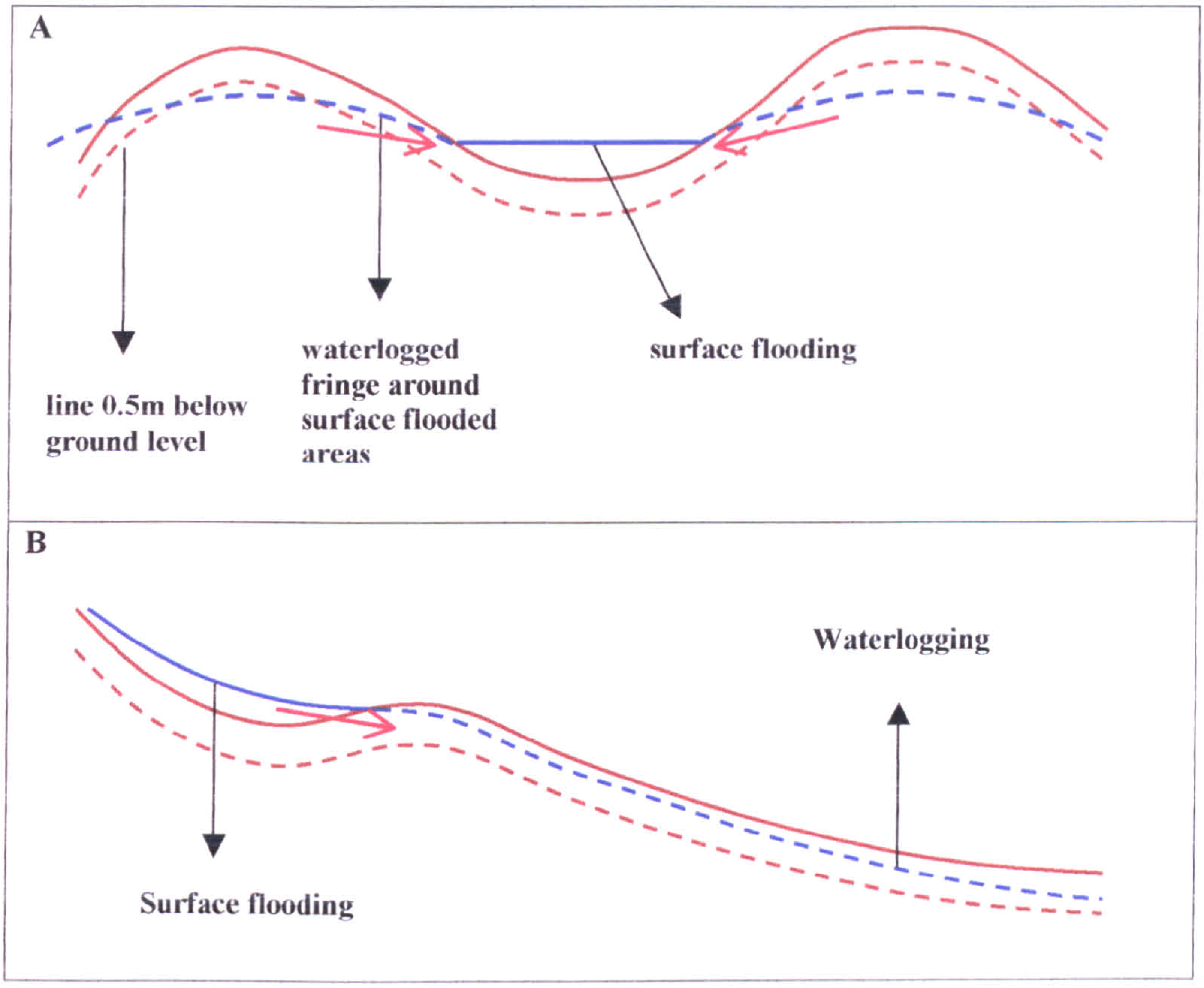


Figure 7.17: Representation of waterlogged areas and their relationship with surface flooding. A: cross section profile. B: longitudinal profile.

iSISMOD would also bring a significant advantage to assess the duration of waterlogging situations, which will be governed by the duration of water standing at the surface. Provided a detailed vertical schematisation is included in the model, an assessment of the impact that water standing at the surface could pose over the saturation of soil layers could also be performed. This concept would be the basis for assessing the impact in wetlands of drainage and groundwater abstractions schemes.

7.7 Is this Model Valid?

This thesis so far has analysed different approaches for simulation of GW-SW in terms of its strengths and weaknesses to support practical applications concerning catchment management plans. Although Chapter 5 reported –from the IMP studies- satisfactory calibration results for the rainfall-runoff model and the regional groundwater model, the fundamental question of model validation and its potential for making predictions was not addressed in detail. Leaving this topic for one of the last sections of this thesis was done on purpose to reflect some tendency in the consultancy field to be more concern with making predictions without worrying too much about validation as expressed by a typical Consultant within the discussion of Beven (2001).

Several issues concerning model validation have been addressed throughout the work done by Anderson and Bates (2001), in which the citations included by the authors provide useful insight into some terminology commonly adopted: calibration, history-matching, validation, credibility, sensitivity testing, etc. Anderson and Bates framed the discussion with two key statements: the relative immaturity of the hydrological science and the fact that hydrology is not a data-rich science.

How can we provide evidence in relation to the validity and predictive potential of the modelling exercises carried out within the Salado basin? Chapters 5 and 7 analysed strengths and weaknesses of MODFLOW and iSISMOD and it can be anticipated that both modelling tools are capable of producing useful and practical deliverables to support a catchment management plan. But usefulness and practicality do not necessarily imply validity, credibility and predictive potential.

The lack of a monitoring network in the Salado basin is an essential point that must precede any discussion of validation. This, in relation to modelling GW-SW interaction within the northwest region, translates in the absence of flow measurements in the trunk drainage collector (Jaureche-Mercante-Italia) and continuous time series of groundwater heads. Only some measurements of groundwater levels are available at Pehuajó together with some measurements of surface water level at the Hinojo-Las Tunas lakes. The issue of data is further emphasized if it is noted the uncertainty in the real location of the gauging sites, as some of them are no longer operational and some sites were removed.

To address certain aspects of model validation, an analysis of groundwater hydrographs for an observation point in Pehuajó was performed. Hinojo-Las Tunas was discarded as an observation point as it is just located in the southern boundary of the test area model and would be influenced by the boundary groundwater heads obtained from the regional model. Even if these lakes had been included within the test area, most of the tributary catchment still would be outside and therefore any surface water level predictions for this lake would have been underestimated.

Figure 7.18 presents a comparison of the groundwater heads obtained with the regional model at 5000m and 500m resolution. In both cases a time series of monthly infiltration was used as the stress to the model. The groundwater head hydrograph obtained with the model at 5000m resolution shows elements of coincidence with the observed levels, mainly in relation to the reproduction of the rising trend. The latter is, indeed, very dependable on how good the initial starting head was estimated, as observations at that time (1960) were not available. However it is rather difficult to make a conclusive statement on how good the model reproduced seasonal groundwater fluctuations. The results obtained with the model at 500m resolution indicate that the observed rising is not reproduced. This is clearly a reflection of the functioning of the evapotranspiration module of MODFLOW and the difference in cell-average ground elevation that results from the change of resolution (approximately 1m, Figure 7.18). A lower ground level (as used in the 500m-model) implies that the model can enter faster in the evapotranspiration zone (between the surface and a depth 3m below it). Groundwater heads are kept within this region due to the nature and assumptions of the evapotranspiration module of MODFLOW (see Chapter 5, Figure 5.6). The parameter that controls the evapotranspiration from the unsaturated zone (see Chapter 5, section 5.2.6, point ii) and, probably, the extinction depth should be adjusted to get the rising trend, what would obscure the physically basis of the model. Despite the regional model reproduces a rising trend, it predicts groundwater heads well below the ground level (approximately 1m for the flood event in 1987/1988) and, therefore, rises the issue of its validity for prediction of flood/no flood situations over an area of 25km^2.

Figure 7.19 presents groundwater levels predicted by iSISMOD at La Salada, using daily infiltration and rainfall time series. La Salada is a lake located 3km north of Pehuajó. This place was selected as it falls within a flood cell, whereas Pehaujó does not. Just for comparison purposes, the observed groundwater heads from Pehuajó were also included in Figure 7.17. Although it is not possible to make a comment on the goodness of fit of any of the surface water levels with the observed values, it can be noted that iSISMOD (and MODFLOW) underestimates the time that heads persist at a high level. This reinforces the ideas analyzed in previous sections in relation to: (i) the need to vary the vertical conductivity spatially and (ii) the need to include direct rainfall and evaporation over saturated surfaces.

Chapter 5 (Figure 5.7) showed that a satisfactory agreement between the distribution of groundwater heads predicted by the model and the one generated from a good set of groundwater head measurements in the northwest region. In a flatland area, strongly controlled by a vertical water balance, it is expected that the groundwater head distribution follows the ground surface. Therefore the strength of this agreement is probably more correlated with the good representation of the DEM, not providing a strong argument to the cause of validating the model.

Previous sections demonstrated that the use of iSISMOD is the correct way towards reproducing areas subject to groundwater-induced surface flooding. In the absence of any detailed measurements, observed flooded areas at a regional and sub-regional level, become a very valuable source of data to assess the performance of the model.

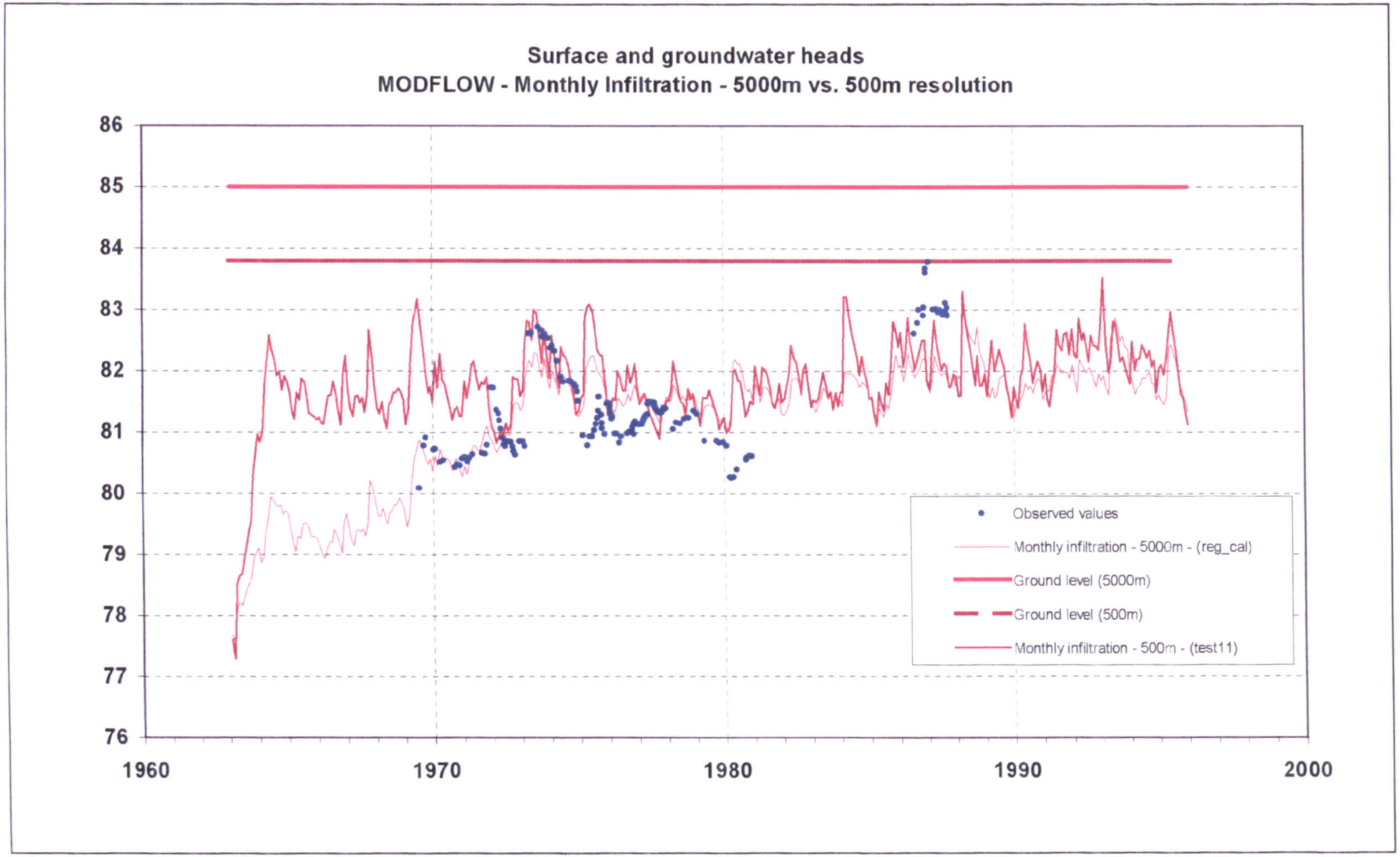


Figure 7.18: Surface and groundwater heads – MODFLOW – Monthly infiltration – 5000m vs. 500m resolution.

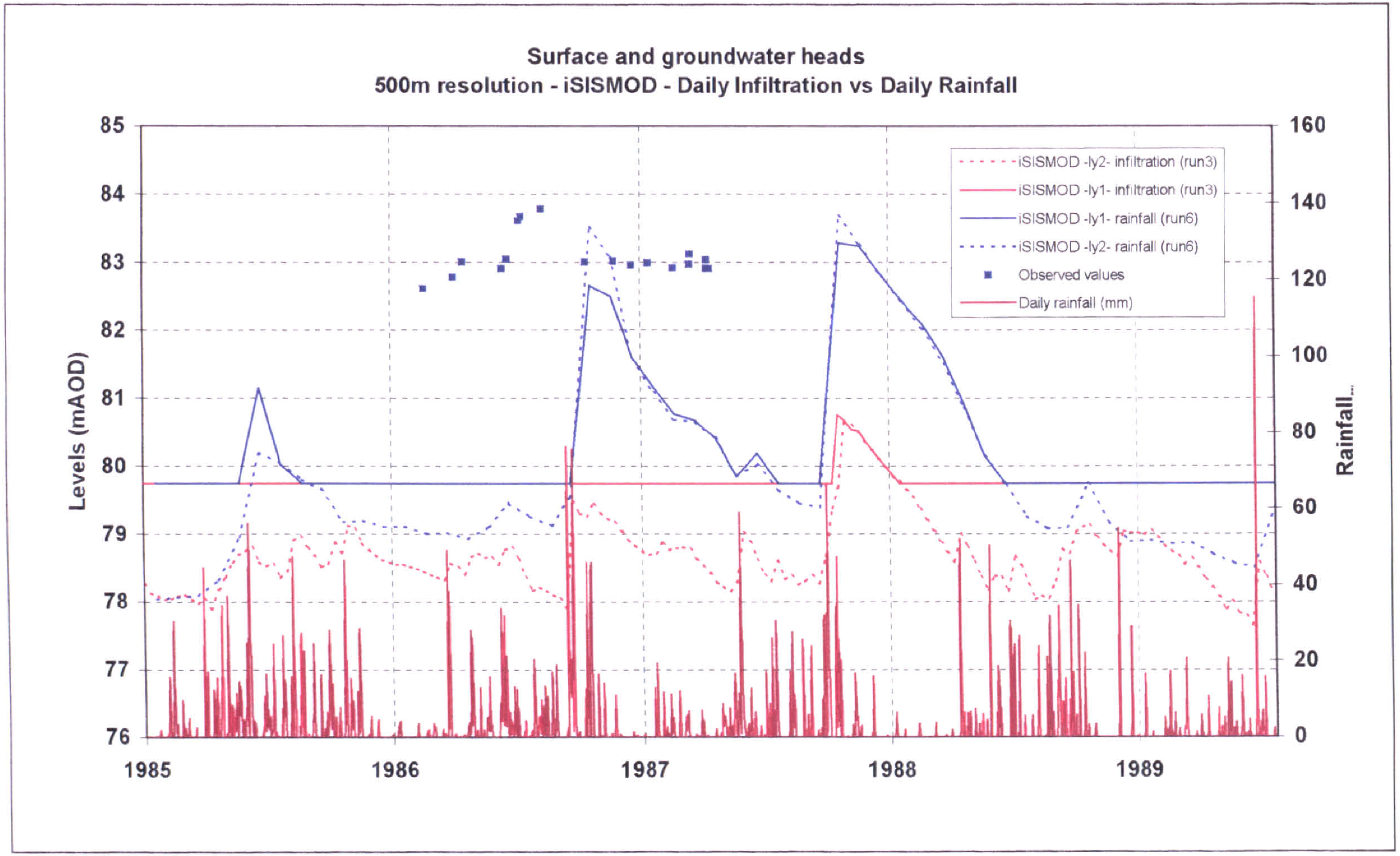


Figure 7.19: Surface and groundwater heads – iSISMOD – Daily infiltration vs. Daily rainfall–500m resolution.

The above paragraphs are sufficient to conclude that there are significant elements that condition the validity of this model. Some of them are inherent to the limitations of current modelling practices to reproduce some of the physical processes related to GW-SW interaction; others are related to the lack of data in the region. This, in some respect, could be considered as falling under the two big headings exposed by Anderson and Bates (2001): the immaturity and general lack of data of the hydrological science. In the case of the Salado basin, the validity of the models developed can be questioned in fairly major topics before entering into the more subtle criticism argued by many authors in relation to physically-based models and the issue of the real significance of effective parameters at the grid cell (Beven, 1989; Grayson et al., 1992; Anderson and Burt, 1990).

On the basis that iSISMOD can make a fair prediction of the groundwater-induced surface flooding, a model executed with this program, under the current availability of data, could be used to assess the current level of damage to the agricultural activity in qualitative terms and at sub-regional and regional levels. However, further *history-matching* type of exercises should be carried out to improve the assessment of the model. In particular a new test area model should be set up to simulate all the area draining to the Hinojo-Las Tunas lakes so that predicted surface water levels can be compared to those measured in the lakes. Also the volume of water at the surface predicted by the model could be compared to the volume obtained from processing of satellite imagery. This could provide an indication of uncertainty in relation to the volume of water to be latterly drained by a given scheme of canals. The estimation of the volume of water at the surface could be carried out identifying flooded areas from satellite imagery followed by the determination of surface water levels from association to the DEM.

The predictive potential of this type of model for assessing the impact of a proposed drainage scheme depends more closely of the interrelationship between groundwater heads and surface water levels in the canals; therefore there is a need to estimate those heads more accurately. This takes more relevance as flow to the canals is governed by a small differential head, which will be subject to a large error if there is a small difference in the GW and SW levels respectively.

One of key premises for the development of a catchment management plan is the need to include environmentally sustainable measures. In the Northwest region sustainability implies preserving the existing equilibrium between the groundwater system and the micro relief what creates suitable conditions for development of agricultural activity. Excessive drainage and/or a return to a drier situation could lower groundwater levels to a situation in which the existing depressions would dry out completely, soils would not retain the required level of moisture and the quantity and quality of fresh water in the dunes would diminish. Stakeholders in the region frequently raise their concerns that the Northwest region returns to the situation prior to 1960 when groundwater levels were 7m to 8m below ground surface. They support their argument on the basis of the occurrence of wet and dry cycles of approximately 30-years duration, something with a long tradition in the region as depicted by Ameghino (1886). Some simulations were carried out with the regional model during the IMP studies to test the impact on the system of the occurrence of a 30-year dry cycle. Results obtained showed that a reverse of the current groundwater situation to that encountered in the 1960's would not occur. This asynchronic type of response of the system is mainly a result of the very gentle groundwater flows; hence it is faster for the system to react to a given increase in recharge by accumulating storage than by eliminating the stored water through lateral groundwater flow. However it is interesting to note that although the prediction of the model agrees with what would be physically expectable the schematization of the model is not adequate to simulate the impact of climate variability in the region. This means that, even if the lateral groundwater flow in the region was larger, the model would still predict the current stable fluctuation of groundwater levels in approximately 3m zone below the ground surface. This is consistent with the way the evapotranspiration module of MODFLOW that calculates the actual loss using a triangular profile as explained in Chapter 5. This implies that when recharge decreases and levels drop close to the extinction depth, evapotranspiration tends to zero and heads tend to recover again. Therefore the real predicted potential of the model for analysis of long-term scenarios is also subject of a significant limitation.

7.8 Summary

This final section summarizes how application of the new coupled GW-SW model (iSISMOD) can effectively contribute towards improving the simulation and understanding of interaction between surface and ground water. The summary is presented in three tables (7.3, 7.4 and 7.5), in order to address different thematic blocks, as follows:

- iSISMOD and the key issues highlighted in Chapter 1: scale of processes and scale of catchment area,
- iSISMOD and the key descriptors of groundwater-induced surface flooding,
- iSISMOD and its usefulness at different stages of the planning process.

For each element identified in the table, a ranking was assigned to represent the strengths and weaknesses of the approach adopted. The ranks are:

√	Element just represented by the model
√ √	Element well represented by the model
√ √ √	Element very well represented by the model

Element	Comment	Reference Figure/Text	Overall Ranking
Representation of key driving processes (See description of processes in Section 7.2.2)	Exfiltration (saturation return flow), ponding and transfers on the surface These processes are well captured by the coupled model provided that schematisation of the model captures all of the low depressions formed in each interdunal trough and correctly represents the crests of the parabolic dune field. Saturation overland flow This is achieved by handling in the program what stress should be used in the model, depending on whether a cell is flooded or not. Seasonal expansion/contraction of open surface water bodies The time varying simulation of the surface and groundwater system allows the model to simulate the contraction and expansion of surface water bodies.	Figure 7.6A Figure 7.7B Figure 7.12 Figure 7.13	√√
Scale of the area	iSISMOD ran successfully over the catchment area of 4,900km^2. The key to success lies in the simplified representation of surface water hydraulics, as a more detailed representation would imply smaller time steps, limiting the application to smaller spatial scales.	Figure 7.1	√√√

Table 7.3: iSISMOD and the simulation of large scale processes in large areas.

Scale of the processes	iSISMOD allows simulating of the interaction of a single surface water feature (a river or a reservoir) with multiple aquifer cells. This facilitates the simulation by lumping large volumes of exfiltrated water (saturation return flow) into single surface water features. Dealing with large scales (both processes and areas) also implies that the model will need to deal with different time steps to accommodate the characteristics of each physical system. iSISMOD was developed so that the numerical stability of the system can be preserved, while still conserving mass.	Section 7.3	√√√

Table 7.3 cont.

Element	Comment	Reference Figure	Ranking
Flood pattern	iSISMOD improves the representation of flood pattern as it is able to simulate the cascading effect of the exfiltrated water draining around or over specific terrain features. Therefore, the program is able to reproduce a key feature of the flood pattern such as increased flooding area/depth downstream as the magnitude of the event increases. The use of a 1D surface water model implies that some floodable areas can be missed out in the schematization, as the entire surface is not included in the model.	Figure 7.14	√√
Flood extent	iSISMOD improves the prediction of flood extent, but the results obtained from the specific applications carried out for the test area show large uncertainty in terms of the input data used to stress the model. The analysis carried out suggested the importance of including in the program the simulation of runoff over variably saturated areas.	Figure 7.9 Figure 7.10 Figure 7.12	√√

Table 7.4: iSISMOD and the simulation of the key features of groundwater-induced surface flooding.

Connectivity and thresholds	iSISMOD improves the simulation of the connectivity and thresholds by including the surface controlling features (crest of parabolic dunes, low pathways along the interdunal troughs, etc.) in the surface water model. As noted above, missing out some terrain features in the model schematization could lead to some under prediction of this problem.	Figure 7.11	√√
Flood duration	This is the aspect that showed the least improvement with iSISMOD, as applied to the test area with the configuration described in previous versions. This problem was identified and analyzed and it is suggested that a finer parameterization is carried out in order to simulate the varying vertical leakages between the top and bottom of the dunes.	Figure 7.13	√√

Table 7.4 cont

Element	Comment	Reference Figure	Ranking
Baseline studies	iSISMOD improves representation of the frequency with which areas are flooded as it is able to predict the occurrence of flooding in downstream areas as a consequence of the movement of the return flow along the interdunes. However, the accuracy of the ultimate product (the flood probability map) depends on method used to estimate flood frequency. If a single annual flood/no flood check is performed then the benefits of using iSISMOD will not be realized. Flood probability maps based on 'peak over threshold' analysis would demonstrate that iSISMOD is a better tool to support the calculations.	Figure 7.14	√√√
Options appraisal	iSISMOD can substantially improve the appraisal of drainage options as it is able to simulate the functioning of surface drainage channels. This implies that drainage density and drainage spacing could be explicitly simulated in the model. However, explicit simulation of surface water hydraulics in the drainage channels may limit the application to large scale analyses.	Figure 7.15 Figure 7.16	√√

Table 7.5: iSISMOD as part of key stages within integrated catchment planning.

- CHAPTER 8 -

PROPOSED FRAMEWORK FOR MODELLING STUDIES AS PART OF INTEGRATED CATCHMENT PLANS

8.1 Introduction

This chapter closes the research by linking all the issues and lessons learnt throughout the research in relation to GW and SW interaction, in order to address the main objective established in Chapter 1: *the development of an outline framework for conducting modelling studies as part of Integrated Catchment Management Plans.*

The literature review focused on analysis of current approaches to dealing with GW and SW interaction, but with the ultimate objective of identifying integrated methodological approaches for catchment studies, rather than attempting to produce a critique of the vast number and variety of modelling tools now available. The outcome revealed a noticeable increase in awareness of the importance of carrying out integrated studies for catchment management plans in order to achieve sustainable solutions. The requirement to generate outcomes for a range of disciplines leads to the development of ever more complex mathematical models that seek to simulate as closely as possible the physical processes that occur in nature. A further step in the model development process can be perceived through the research carried out as part of the Harmon IT project (HR Wallingford, 2002), where a clear emphasis is placed on integrating models and designing open interfaces that can work in a trans-boundary environment and which have a high degree of flexibility to accommodate different modelling packages.

However, the literature review also showed that it is equally important to develop a methodological platform to drive the selection of modelling approaches, tools and linkages. This is necessary, for three main reasons. First, to allow the deliverables that are actually required to support integrated catchment studies to guide the development process Second, to avoid committing monetary and human resources unnecessarily. Third, to ensure that the complexity of the modelling is compatible with the requirements of decision-makers at each stage of the exercise.

While the literature demonstrated the importance of such a platform or framework, it also revealed the absence of any suitable examples and, therefore, this research aimed at fill this gap. Grayson et al. (1992), in his questioning of the usefulness of physically based models (in his current condition), highlights that the development of tools to deepen the understanding of processes must continue, but for management purposes their usefulness will remain limited. And goes further in saying that simpler approaches that consider the most important factors that characterize the response of the basin (see parallel with Mitchell, 1989), may be more appropriate to the level of available data for the majority of decisions.

In this context, the next section reviews the key issues and lessons learnt during the Integrated Master Plan (IMP) studies, further expanded and analysed in this research, leading to the description of the proposed framework in Section 8.3.

8.2 Proposed Framework for Modelling Studies

The Framework for Catchment Modelling Studies (FCMS) proposes that *a staged and systematic approach to be used as a template for the development of modelling exercises to suit the physical characteristics of a basin and the level of detail required at each stage of a project, trying to strike a balance between project needs, cost and human resources.*

The development of catchment-wide mathematical models is a process that is tightly coupled with a number of factors such as hydrometeorological input, dominant hydrological processes, geomorphic characteristics and type of outputs required. This effectively precludes production a manual for model development. Rather, the proposed FCMS attempts to stand above issues related to the model building process and assist the basin planner by guiding him or her through a systematic thinking process concerning modelling needs, approaches and outcomes. In other words, the application of the FCMS would, indirectly, permit planner to address systematically the different issues discussed in the previous sections.

The proposed FCMS is a general template for the planning process, but its presentation will be illustrated using the research outcomes of the analysis of GW-SW interaction in the study area.

Although this research was focused on and applied to a large catchment, the structure and proposals underpinning this framework should be generally applicable to other basins with geomorphic and scale characteristics different to those of the Rio Salado Basin.

The FCMS recognises three distinct blocks of activities, coinciding with the three stages proposed by Mitchel (1989) to guarantee a timely and cost-effective planning process. The blocks are: a normative level that focuses in the general issues of the integration of the water system with other systems; a strategic level that looks comprehensively at issues of land and water interaction, and; an operational level that focuses on actual integration between selected key processes in the basin (Figure 8.1).

The proposed FCMS parallels existing approaches to geomorphic studies, environmental assessments and engineering project management (Thorne, 1998). In particular, one of the lessons learnt from the research studies was the need for a close relationship between geomorphic features and mathematical modelling. For example, the proper representation of different dune fields identified in the Northwest region are essential for the simulation and understanding of GW-SW interaction that drives the flooding in the test area. Similarly, within the context of the IMP, study of the origin and morphology of landforms along the Rio Salado allowed identification of severe constrictions that naturally impede the conveyance of flood flows, which in turn led to an important criterion in schematising the surface water model (iSIS).

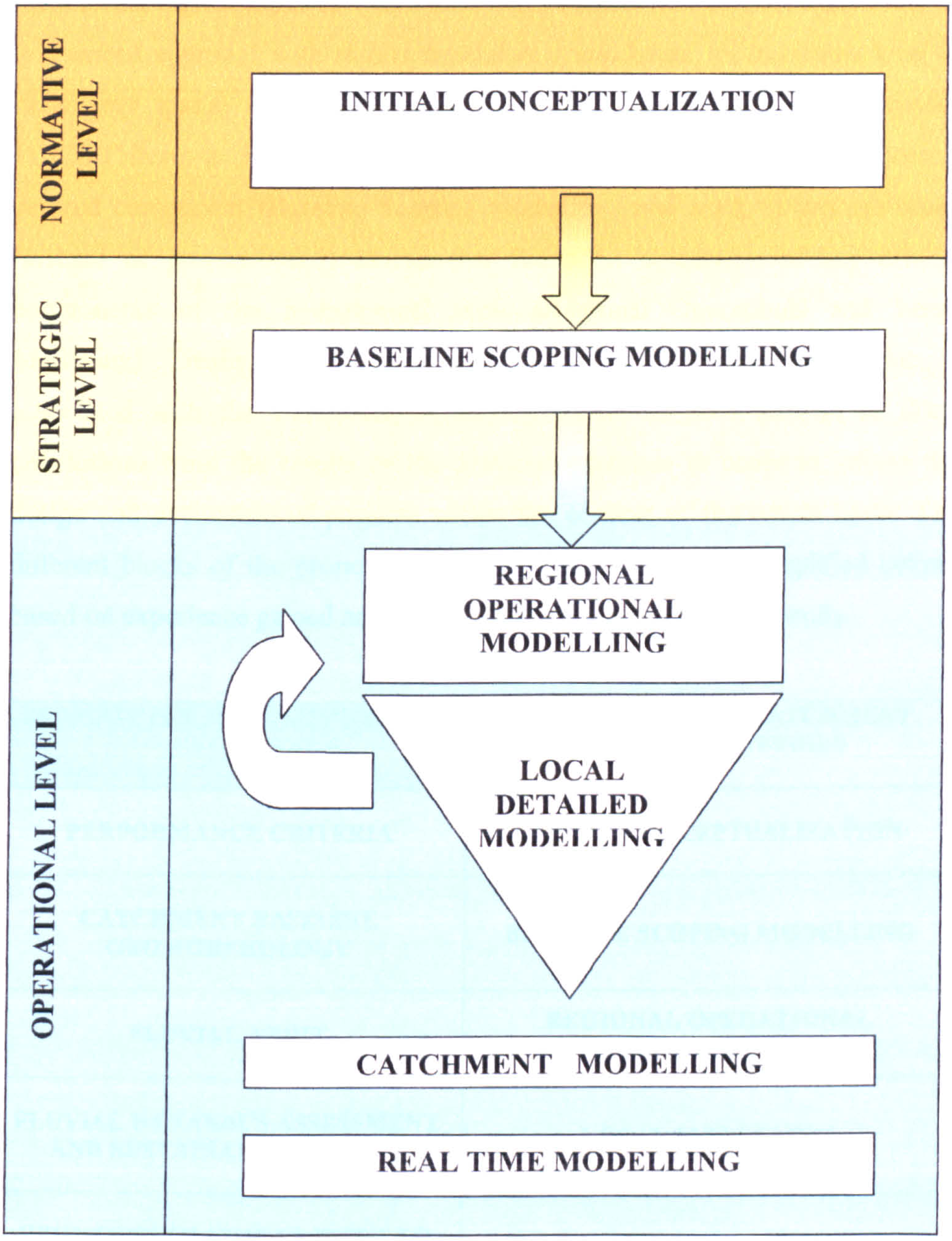


Figure 8.1: Framework for Catchment Modelling Studies (FCMS)

The structured approach for geomorphic studies is presented in Figure 8.2. This approach distinguishes two broad categories: a strategic overview of the basin (Catchment Baseline Geomorphology) and a set of project-centred studies (Fluvial Audit, Geomorphological Dynamics Assessment and the Geomorphological Input to Water Resources Projects). It also includes a staged and nested approach with results dependent components, an increasing level of detail and spatial resolution, but a decreasing spatial extent. The proposed FCMS follows a similar logic, distinguishing between a strategic, catchment-centred component (Baseline Scoping Modelling), and a set of process-based (instead of project-based) blocks that focus on simulation of key driving components of the hydrological cycle (Regional Operational and Local Modelling). Finally, the Geomorphological Input to Catchment Studies is associated with the Catchment Modelling Block, as both attempt to draw conclusions from the results of the previous exercises in order to inform the design and evaluation of projects within the context of the whole basin. The different blocks of the proposed FCMS are described and exemplified below, based on experience gained and results generated in this research study.

FRAMEWORK FOR GEOMORPHIC STUDIES	FRAMEWORK FOR CATCHMENT MODELLING STUDIES
PERFORMANCE CRITERIA	INITIAL CONCEPTUALIZATION
CATCHMENT BASELINE GEOMORPHOLOGY	BASELINE SCOPING MODELLING
FLUVIAL AUDIT	REGIONAL OPERATIONAL MODELLING
FLUVIAL DYNAMICS ASSESSMENT AND SUSTAINABLE DESIGNS	LOCAL MODELLING
GEOMORPHOLOGICAL INPUT TO WATER RESOURCES MANAGEMENT	CATCHMENT MODELLING
POST PROJECT APPRAISAL	REAL TIME MODELLING

Figure 8.2: Parallel between the proposed FCMS and the approach for Geomorphic Studies (Thorne, 1998)

8.2.1 Initial Conceptualisation

8.2.1.1 Objectives

This first block of the FCMS aims to establish the relationship between project objectives, disciplines involved and modelling requirements necessary to support each of the disciplines. If applicable, modelling requirements at different stages of the project should be identified.

8.2.1.2 Sample Techniques

- Review all background information related to the project in order to see beyond the client's requirements as stated in the ToR, identifying the real underlying needs of the project. *What is really required from the modelling discipline? What does the client really need (noting that this may not necessarily agree with what he or she initially requested)?*

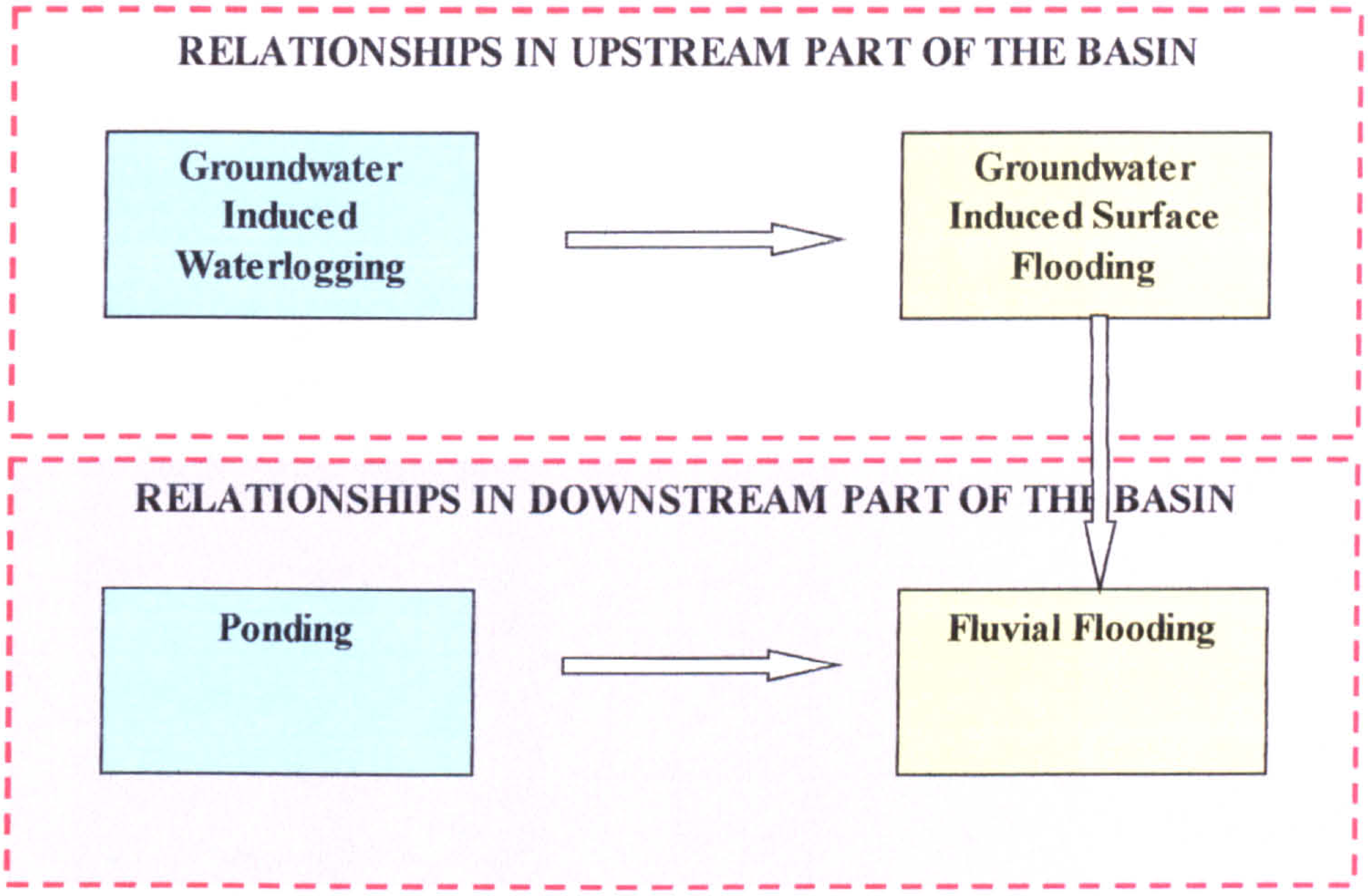
- Definition of conceptual risk model(s) to interpret the hazards, exposures and vulnerabilities in the basin, encompassing economic, environmental, and social dimensions.

- Definition of linkages between risk model(s) and mathematical models in order to establish how tools will support practical risk analysis.

- Definition of a matrix to establish the links between disciplines and modelling needs.

Box 1 presents the link between risk models established for the Rio Salado basin, and Box 2 exemplifies a disciplines-modelling matrix.

Box 1: Initial Conceptualization – ***Establishing links between risk models***



8.2.1.3 Expected Outputs

Having analysed objectives, needs and risk models, this phase of the defines the "catchment theme" and "modelling theme" of the project as the topics that will drive and condition development of the modelling strategy. Box 3 presents an example.

Box 3: Initial Conceptualization – ***Catchment and Modelling Themes***

For the case of the Rio Salado basin, groundwater-induced surface flooding is the dominant process in the economically most important region of the basin (the Northwest) and could defined as the "catchment theme". Therefore, simulation of GW-SW interaction emerges as the associated "modelling theme".

Box 2: FCMS – Initial Conceptualisation – ***Sample summary matrix of project objectives vs. modelling needs***

	Water Resources Assessment	Diagnosis – Flooding	Drainage measures	Flood mitigation measures	Land use planning	River corridor management	Water management at a farm level	Preservation of wetlands	Economic analysis	Operation of water-related structures	Flood Forecasting
Rainfall runoff model	•	•	•	•	•	•	•	•	•	•	•
Overland Saturation Flow		•					•	•			
Open Channel Flow – 1D		•		•	•	•			•	•	•
Floodplain modelling – 2D				•	•						
Groundwater modelling	•	•	•				•	•	•	•	•
Water Quality						•	•	•			
Sediment Transport				•		•		•			

8.2.2 Baseline Scoping Modelling (BSM)

8.2.2.1 Objectives

The objective of the BSM is to identify all the relevant processes and variables that operate at the catchment scale and define the roles they play within the conceptual risk model(s) outlined in the previous block. This, in turn, identifies the processes that should be included in the models, provided they make a significant contribution decision making at each stage of the planning process. The work in this block should be performed in conjunction with catchment baseline reconnaissance at the planning and initial diagnosis phase. In understanding the macro processes (i.e. overall water balances) simple modelling exercises should be set up for scoping the next steps.

8.2.2.2 Sample Techniques

The type of analysis tools required in this block would fall into the category of "interpretive" or "generic" rather than "predictive" models (Anderson, 1997), the main difference being that the first two do not necessarily require calibration and would mainly be used to guide development of a conceptual framework for exploring sensitivities to different future scenarios.

Examples of modelling approaches would include:

- development of lumped rainfall-runoff models,
- simple tank model at a sub-regional level,
- coarse 3D groundwater models,
- GIS-based regression models linking inputs (hydrometeorological data) with outputs (groundwater head response).

8.2.2.3 Sample Outputs

Beside the modelling exercise, the outcome of this stage is a comparative matrix with which to test the knowledge acquired of the interaction between the different physical processes of the basin. An example is presented in Box 4.

Box 4: Baseline Scoping Modelling – *Comparison* matrix

	Rainfall-runoff	Fluvial flooding	Groundwater induced surface flooding
Rainfall-runoff		3	3
Fluvial flooding	1		1
Groundwater induced surface flooding	3	2	

Key:

1 **Process A has low impact on Process B and no coupling is required.**

2 **Process A has medium impact on Process B and a weak coupling is required.**

3 **Process A has high impact on Process B and a strong coupling is required.**

Interpretation of the matrix presented in Box 4 indicates the need to focus on the following process relationships:

- surface runoff has high impact of fluvial flooding and a rainfall-runoff model should be developed to provide inputs to a river model along fluvial corridors. This leads to the coupling of HYSIM with iSIS Flow.

- rainfall has a strong and direct influence on generation of groundwater-induced surface flooding through infiltration to the soil and aquifer layers. This leads to the coupling of HYSIM with MODFLOW.

- groundwater-induced surface flooding also has a strong influence on the generation of surface runoff as the impermeability of the ground surface increases and saturation overland flow occurs. This leads to the inclusion of a component in the rainfall-runoff-aquifer model to account for the increase in runoff as groundwater exfiltrates to the surface.

- groundwater-induced flooding and fluvial flooding are coupled through sub-regional boundaries, but the coupling within a sub-region is weak.

Once linkages between processes have been identified, it should be determined whether they operate at a regional, sub-regional or local scale. A sample output of this exercise is presented in Box 5.

Box 5: Baseline Scoping Model – *Identification of scales at which key linkages operate*

Process 1	Process 2	Dominant Scale
Rainfall-runoff	Fluvial flooding	sub-regional – i.e. fluvial corridor Rio Salado
Rainfall-runoff	Groundwater induced surface flooding	sub-regional – i.e. Northwest region (Test Area)
Groundwater induced surface flooding	Rainfall-runoff	sub-regional – i.e. Northwest region (Test Area)
Groundwater induced surface flooding	Fluvial flooding	Transfer between sub regions

Finally, the BSM should end with definition of the modelling strategy and specification of the steps necessary for development of more detailed (in terms of processes simulated) mathematical models.

8.2.3 Regional Operational Modelling (ROM)

8.2.3.1 Objectives

The purpose of operational modelling is to concentrate on the simulation of the main processes identified in the Baseline Scoping Modelling block. Operational model/s (mostly carried out at a sub-regional scale) would concentrate on simulation of relevant components of the hydrological cycle, with variable degree of coupling. In the diagnosis phase of the project, the ROM could be used to identify mechanisms driving hazards (i.e. the role of geomorphic controls along a fluvial corridor or the role of crests of parabolic dunes limiting conveyance in the Northwest region) and assess impacts (i.e. through the construction of Flood Probability Maps). At the project stage, the ROM could be used to test the impact of proposed measures at the sub-regional scale.

8.2.3.2 Sample Techniques

- development of physically-based models such as river models, floodplain models and aquifer models,
- sensitivity analysis of model parameters,
- sensitivity analysis to test interaction between processes,
- development of a final Performance Matrix to integrate the outcomes of the analysis carried out in this block. This exercise also serves to prove whether the model(s) are able to perform within the proposed planning scenarios. Box 6 presents an example.

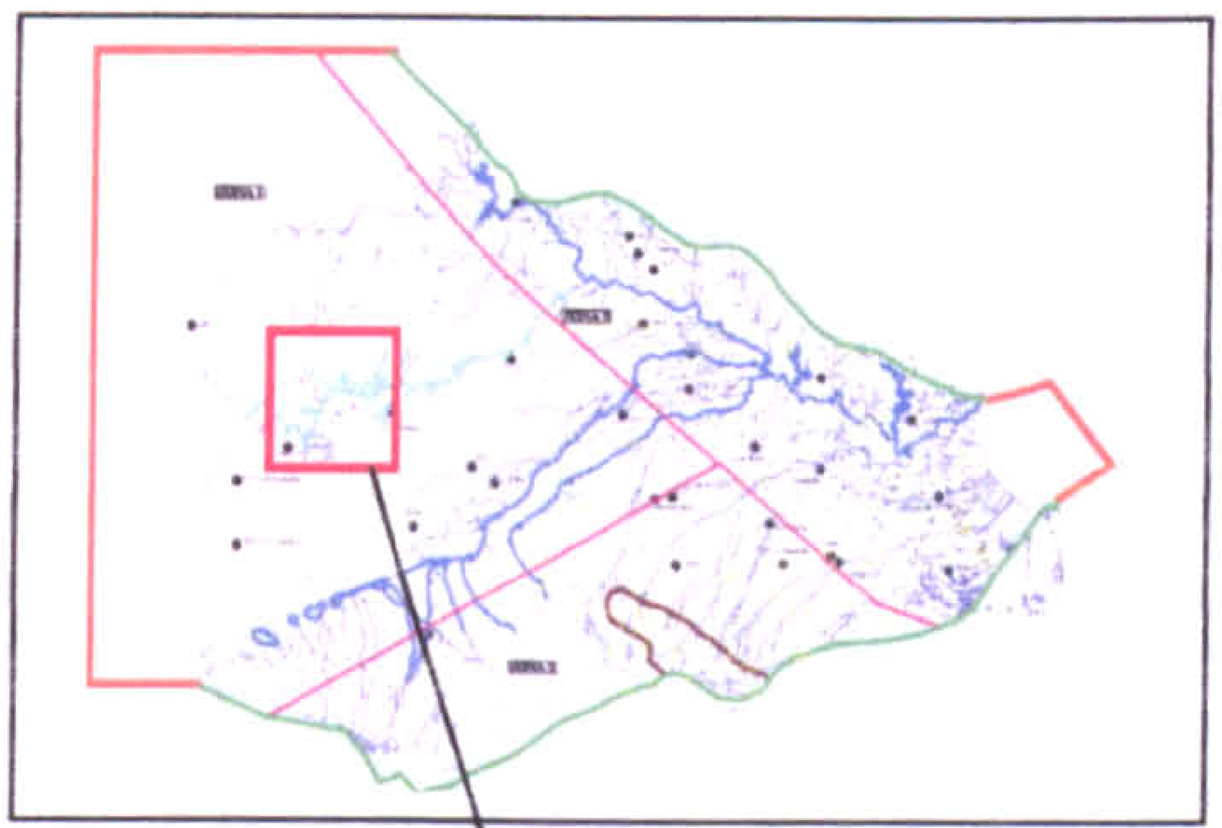
Box 6: Regional Operational Modelling – ***Performance Matrix***

Escenario	Expected output
Change in grid resolution in the regional groundwater model.	A reduction to match the resolution of the DEM would primarily help the prediction of groundwater heads and less so the prediction of areas with surface flooding.
Monthly vs. Daily data entering the regional groundwater model.	The prediction of surface flooding areas is very sensitive to the combination of a temporal and scale resolution.
Sensitivity of groundwater heads to changes in hydrogeological parameters.	Groundwater heads are very sensitive to a change in the extinction depth of the evapotranspiration package of MODFLOW.
Sensitivity of groundwater heads to a step change in the level of surface water bodies.	Groundwater heads are insensitive to changes in surface water levels of existing water courses as they represent a very small proportion of the areal system.
Sensitivity of surface water model to baseflow conditions.	As the main objective of the model is to predict fluvial flooding, results are insensitive to a change in baseflow, should a coupling with an aquifer model be materialised.
Simulation of regional groundwater trends.	A change in MODFLOW evapotranspiration module is required.
Prediction of groundwater induced surface flooding.	MODFLOW alone can be used to predict surface flooding but results are very sensitive to grid resolution and time step of stress time series.
Testing of drainage scenarios.	MODFLOW can only perform a limited testing based on an explicit simulation of drainage canals.
Generation of Flood Probability Maps.	The limitations of MODFLOW to simulate surface processes and identify surface flooding areas translate into important qualifications to this output.

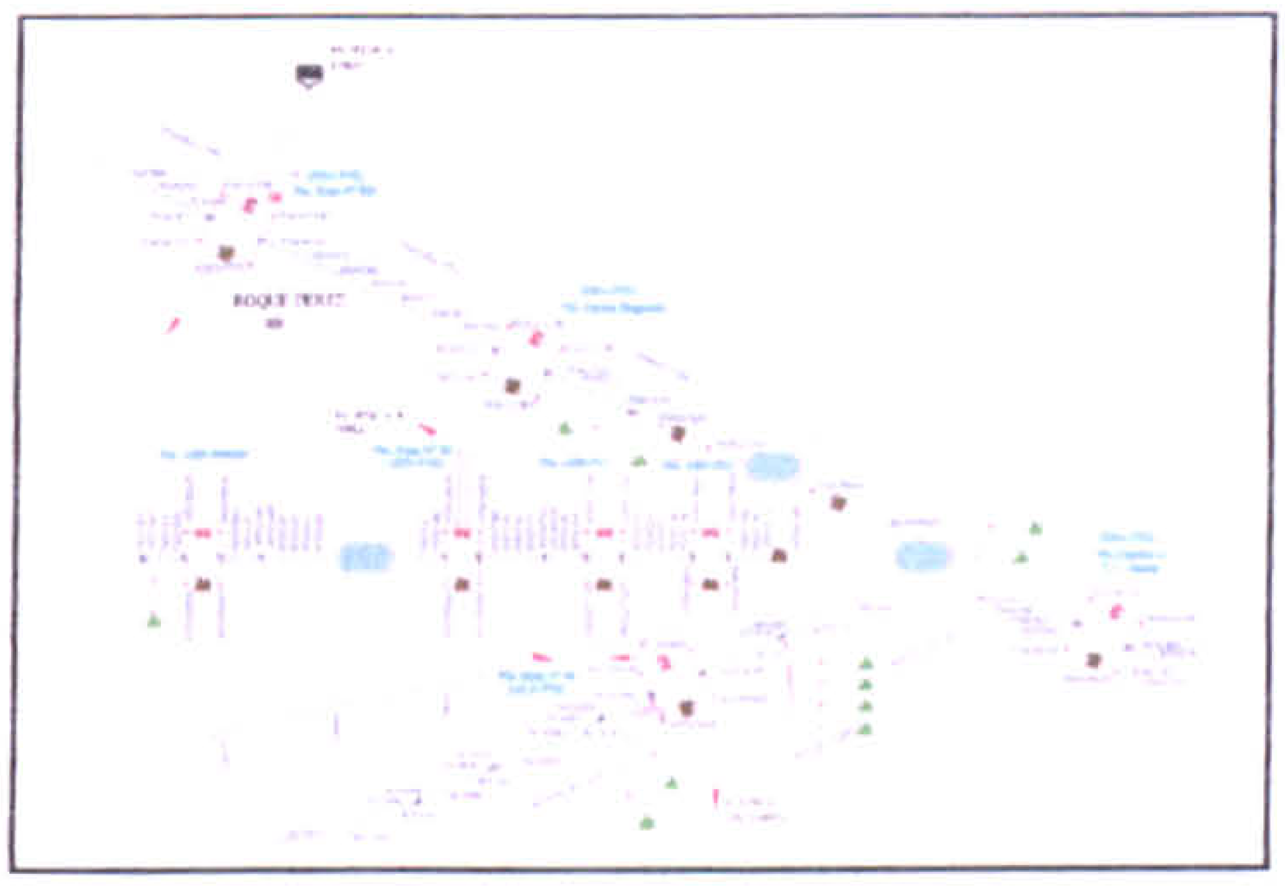
8.2.3.3 Sample Outputs

The key outcome of this block is availability of operational models (see Box 7). An indirect outcome of developing the ROMs and applying them in the diagnosis stage of the project, is the identification of template areas for further detailed analysis and modelling as part of the next block in the framework.

Box 7: Regional Operational Modelling – ***Simulation of dominant processes at a regional level***



Regional Surface Water Model (iSIS)



Regional Groundwater Flow Model (MODFLOW)

Template area (TAM)

8.2.4 Local Modelling (LM)

8.2.4.1 Objectives

Having identified template areas for further study in the ROM block, the objective of the LM block is to model in more detail coupling between processes that is not reproduced in any of the regional operational models. Two specific objectives are linked to this block: to gain a deeper insight into the physical processes of the basin that could then be fed back into one of the operational models (see feedback arrow in Figure 8.1) and; to test engineering options trying to make generalisations that could then be passed onto the final Catchment Modelling block.

8.2.4.2 Sample Techniques

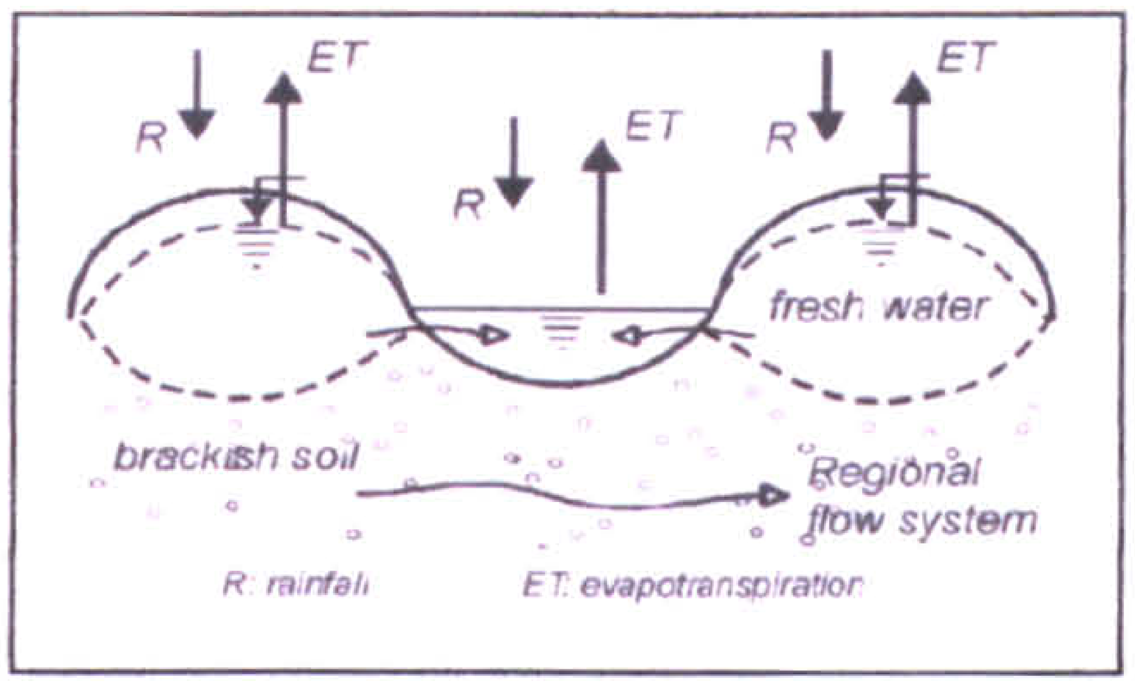
Basically, the same techniques listed in the ROM block applied to Local Modelling but with more emphasis on the use of more physically-based, integrated modelling tools. An example of this could be the application of iSISMOD to simulate coupling between GW and SW in the test area, to predict groundwater induced surface flooding and then analyse the effectiveness of drainage measures.

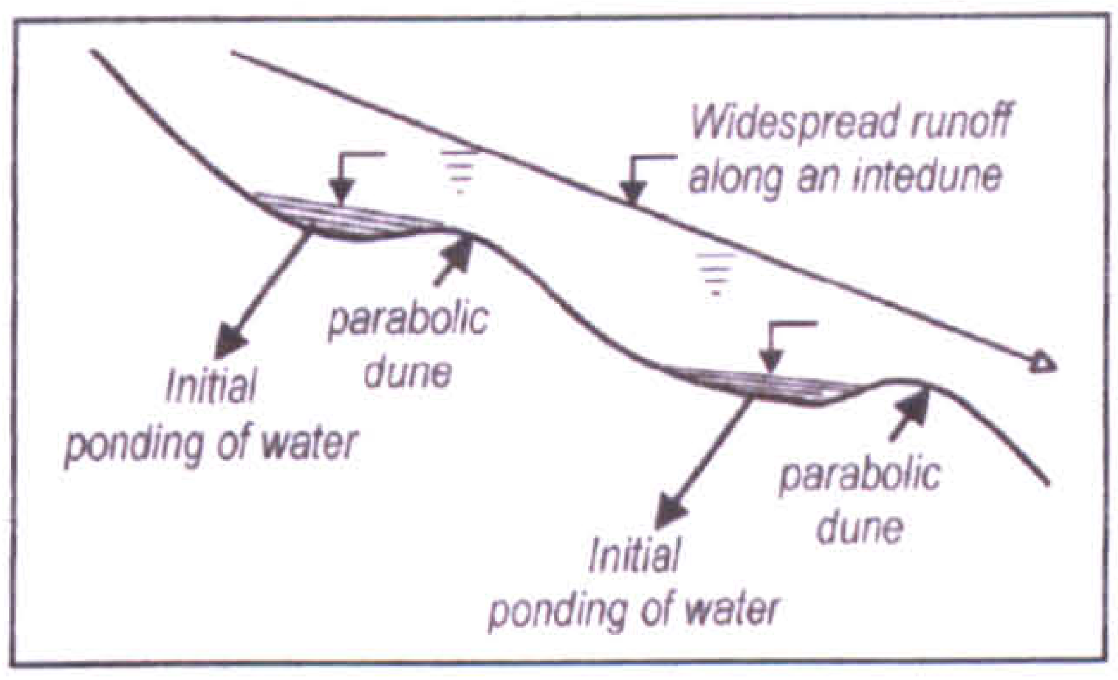
8.2.4.3 Sample Outputs

The main output of this block is a detailed local model for each of the selected template areas and a set of guidelines to extend the conclusions obtained from each model back to a catchment wide basis. Box 8 presents two examples. One is the test area model carried out as part of this research and the other is a proposed local model to analyse the effect of simulating GW-SW interaction in the prediction of fluvial flooding.

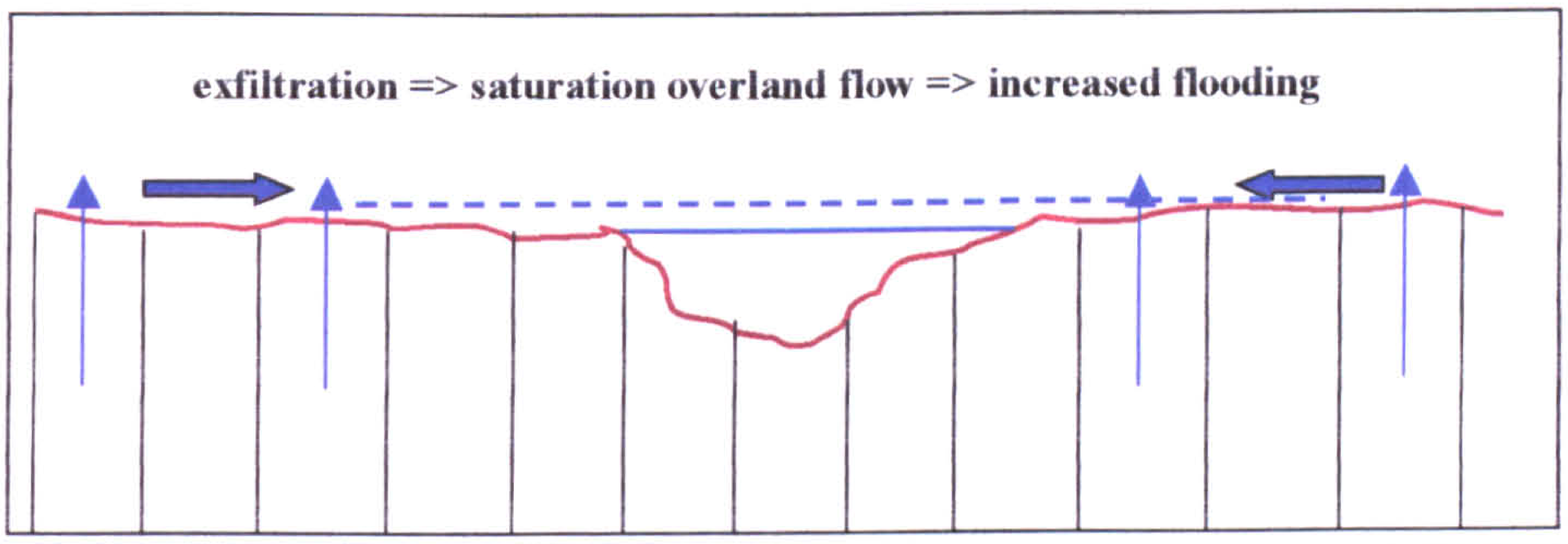
Box 8: Local Modelling – *Simulation of dominant processes at a local level using iSISMOD*

Template A: GW-SW Interaction – Northwest Region





Template B: GW-SW Interaction – Fluvial corridor



8.2.5 Catchment Modelling (CM)

8.2.5.1 Objectives

The Catchment Modelling component does not necessarily imply constructing a new model, but rather modifying any of the previously developed ones to integrate the conclusions obtained from the Local Modelling. It is normally applied at the project phase of the planning process and the main objective is to analyse the impact of any intervention at a basin level after having analysed this using a local model.

In the case of this research, where drainage canals were proposed at a sub-regional level, a local model exercise could be carried out to analyse the optimum solution in terms of return period-cost-mitigation of flooding, aiming at answering questions such as: *What is the optimum type of drainage required? What is the optimum return period? What should be the size of the canals? What should be required drainage density?*

The Catchment Modelling stage aims at more general questions of the type: *What would be the recommended, staged approach for development of the drainage system to minimize downstream impacts? What would be the benefits for the region? What would be the effect of doubling the drainage density into the sub-region?*

8.2.5.2 Sample Techniques

- Modify point-model boundaries to represent the impact of interventions from outside the modelled area. For example, flow-time boundaries could be changed in the surface water model to accommodate the additional flow coming out of a newly drained area.

- Modify arealy-distributed stresses to simulate the effect of interventions that also take place in a fairly distributed way. For instance, implementation of a drainage system will modify the amount of the effective recharge entering the aquifer. Therefore its impact could be represented by modifying the time series of recharge rather than modelling each canal.

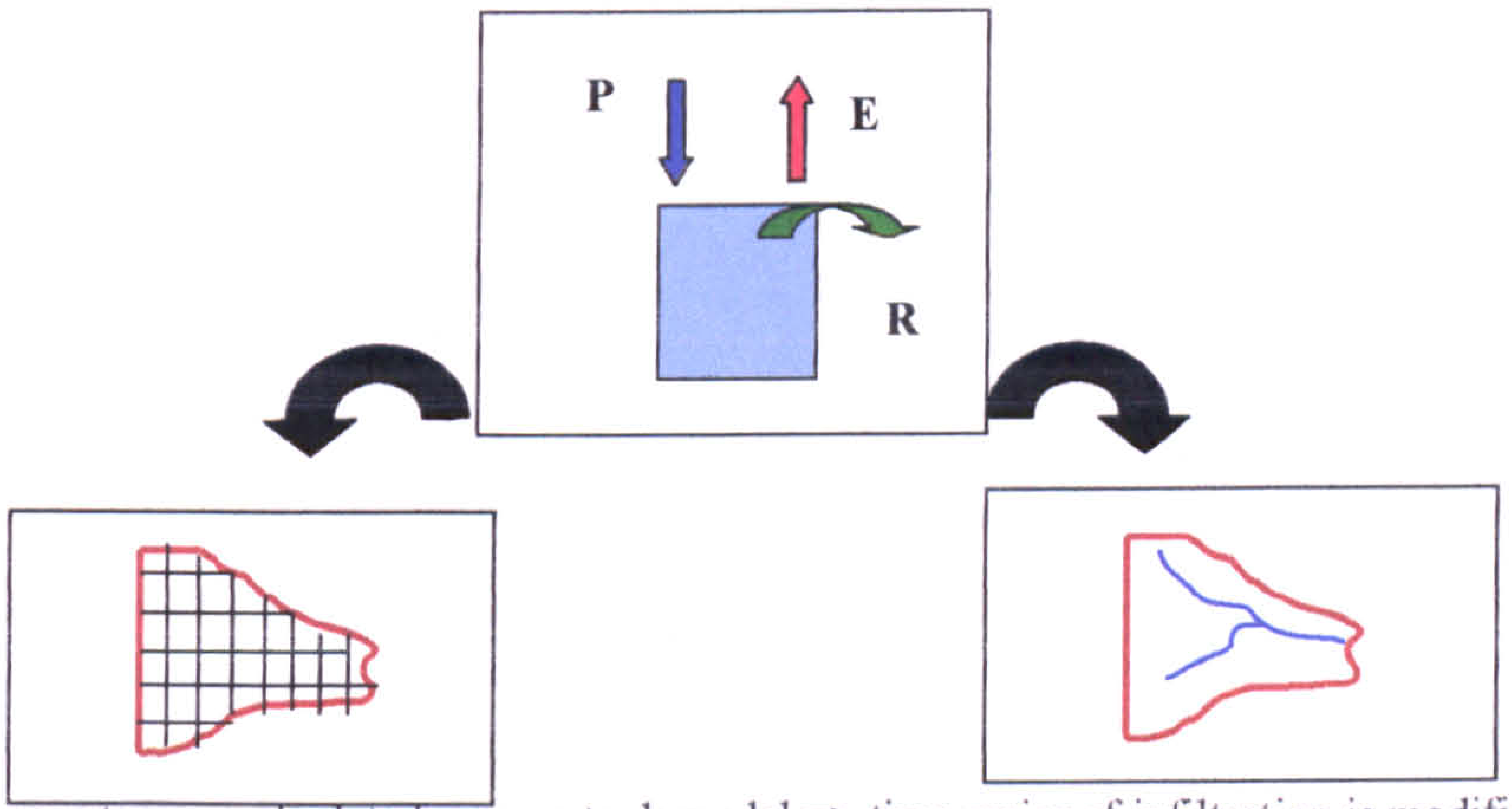
- GIS operations could be used to assist in the extrapolation of the conclusions from the local model to the catchment model. For example, conclusions obtained with a local model could be extrapolated to other areas with similar geomorphic and hydrometeorological characteristics.

8.2.5.3 Sample Outputs

Boxes 9A presents an example of catchment modelling like that used in the IMP studies, whereas Box 9B presents an alternative approach that makes use of iSISMOD applied to a local area.

Box 9A: Catchment Modelling – ***Analysis of impact at the regional level***

Approach A: Regional Operational Models fed by externally calculated drainage rates.

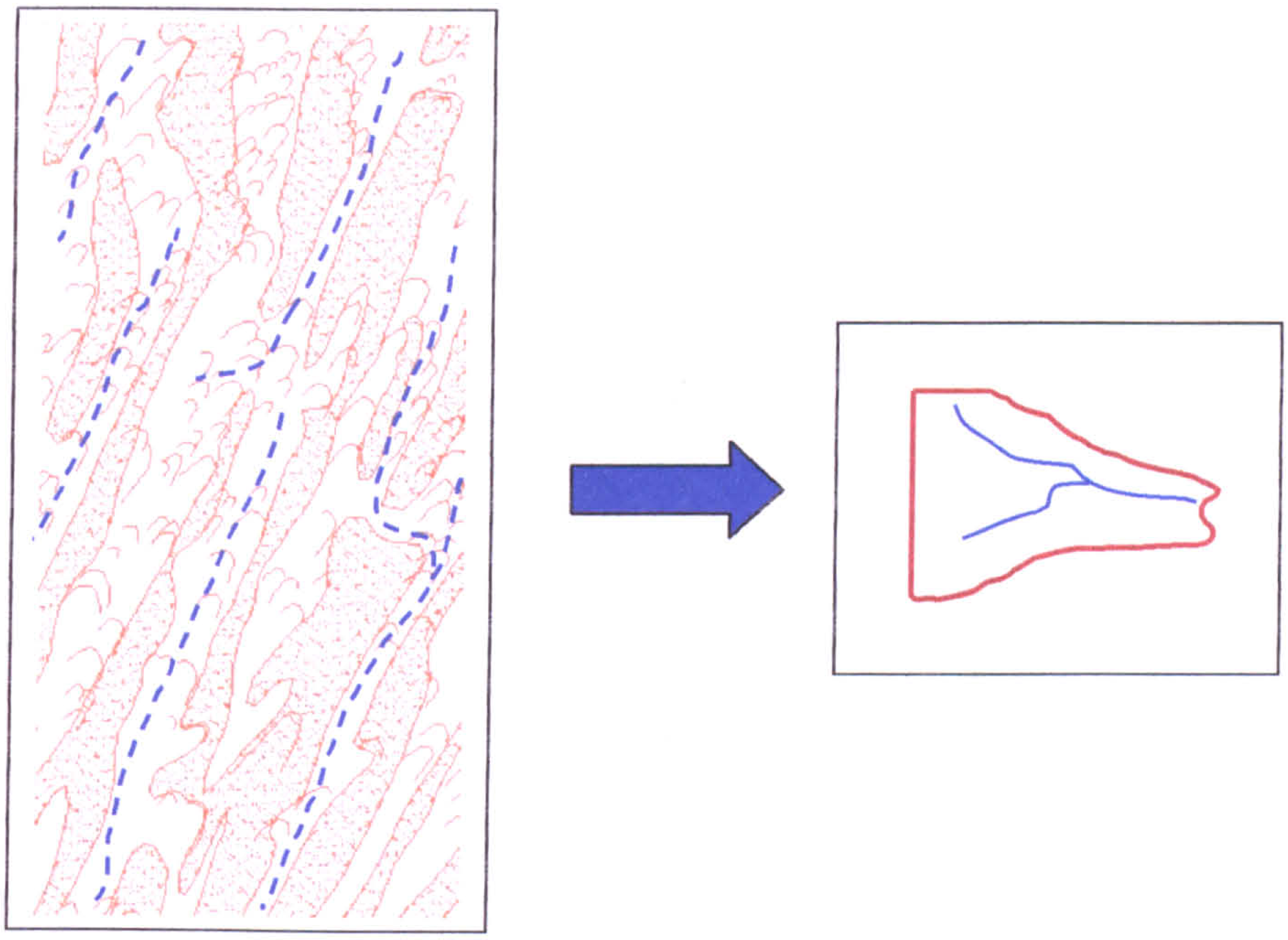


1. Drainage rates are calculated using a tank model => time series of infiltration is modified and applied into the Regional Groundwater Model to assess reduction of induced surface flooding.

2. Drainage rates are calculated using a tank model => flow-time boundary of Regional Surface Water Model is modified to assess impact along the fluvial corridor.

Box 9B: Catchment Modelling – ***Analysis of impact at the regional level***

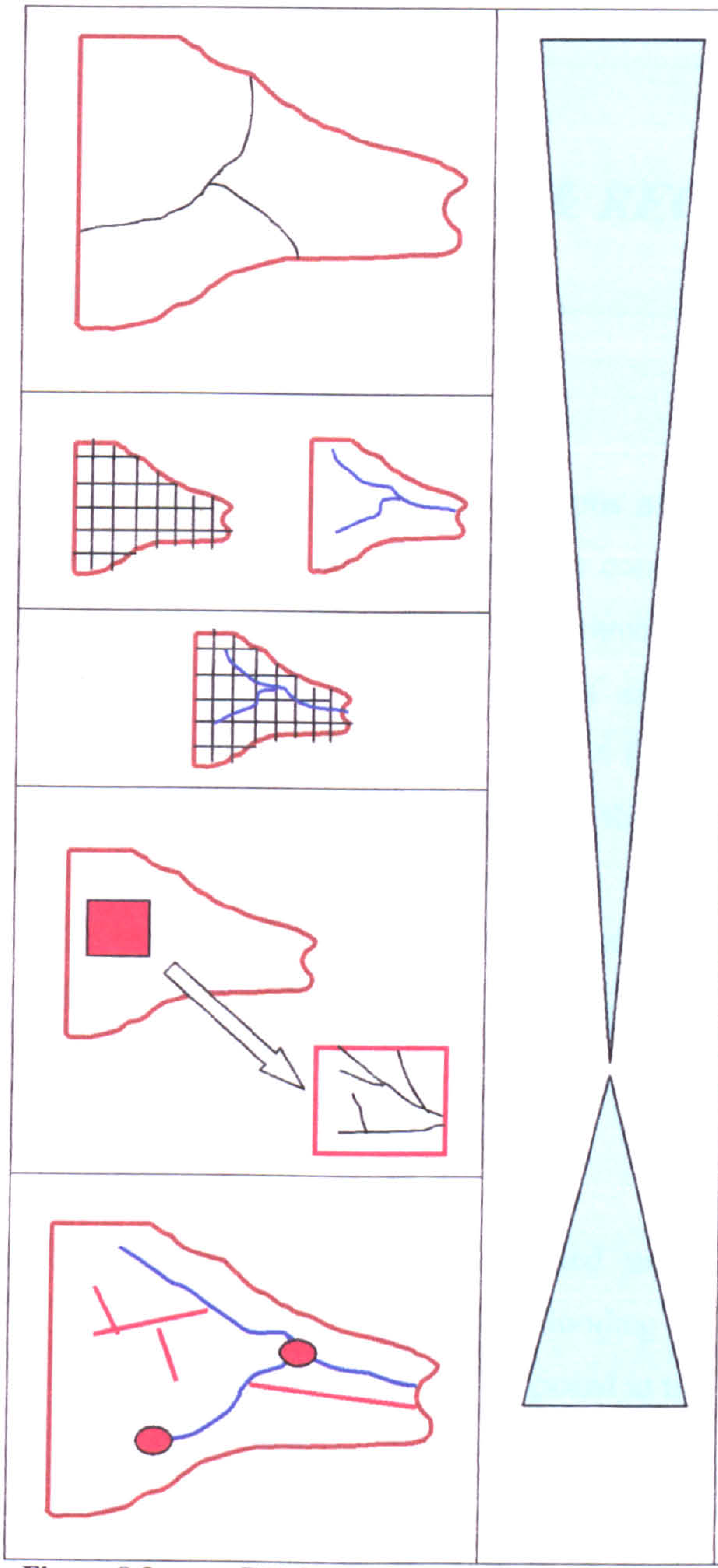
Approach B: Regional Surface Water Operational Model is fed by drainage rates calculated with local model (iSISMOD).



1. Drainage rates are calculated using iSISMOD applied to a local model

2. Drainage rates for other areas are obtained by either other local models or by extrapolation based on geomorphic and hydrometeorological characteristics.

3. Obtained drainage rates are then converted to flow-time boundary for the Regional Surface Water Model to assess impact along the fluvial corridor.



Catchment Baseline Modelling (CBM)

- Full integration
- Broad scale
- Full coupling
- Spatial aggregation
- Identification of processes
- Identification of interactions

Operational Modelling (OM)

- One or more focused process models
- Scale, aggregation and coupling depends on each case.

Local Modelling (LM)

- Generally full coupling
- Reduced scale
- Generally nesting to one of the operational models

Catchment Modelling (CM)

- Broad scale
- Analysis of the impact of measures at the basin level
- As much coupling as possible

Figure 8.3: FCMS – Schematic representation of its application to catchment studies.

- CHAPTER 9 -

CONCLUSIONS & RECOMMENDATIONS

9.1 Overview

This chapter presents the conclusions and recommendations that arise from the research reported in this thesis. The conclusions link the two major topics within modelling to support integrated catchment management that have been addressed in the previous chapters: analysis of different modelling approaches to simulate GW-SW interaction; and proposal of a framework for catchment modelling studies (FCMS). Throughout the thesis, the Rio Salado basin and the IMP studies have provided a template for analysis of GW-SW interaction and case study for development of the framework. It was research and practical issues identified during the Salado basin modelling investigations that stimulated the research performed in this study and generated fundamental questions to be addressed including:

(i) Were the results obtained using uncoupled GW-SW modelling of ground-water induced flooding in the test area actually sufficient to justify the measures proposed in the IMP study?

(ii) To what extent did the approach adopted in the IMP studies for the Rio Salado Basin constitute an integrated modelling strategy?

(iii) Accepting that the approach adopted was not fully integrated or co-ordinated, were the results obtained compromised by the modelling approach adopted?

(iv) Based on the answers to questions (i) to (iii), how could the analytical basis and framework used to support the IMP be modified to improve the accuracy and reliability of its findings?

While the inspiration and practical basis for the research reported in this thesis came from the Rio Salado Basin, the conclusions reached have wider applicability and the findings provide insights that support broader recommendations for further research. It is in this spirit that the remainder of this chapter attempts to generalise the main conclusions and recommendations that represent the major outcome of the work.

9.2 Conclusions

- The major conclusion to emerge from the literature review was that no structured approach currently exists within which to perform modelling studies to support integrated catchment management planning. This deficiency is mainly of relevance to large basins where, besides the need to reconcile the objectives of different disciplines, there also exists the need to overcome the difficulties inherent to modelling a variety of geographical regions within the same basin.

- The decision of the World Bank to commission a single, integrated catchment management plan for the entire Rio Salado basin was the springboard for this research. This unique flatland of 175,000km^2, located in the Buenos Aires Province of Argentina, periodically suffers extensive flooding that seriously limits the potential for agricultural and livestock development of what is, economically, the most important region of the country. As Technical Co-ordinator responsible for development of an Integrated Master Plan (IMP) and engineer in charge of the modelling activities, I became fully aware of the challenges faced in dealing with such a large basin and the limitations of currently available models and modelling strategies. Specifically, through the three-year IMP project I came to appreciate the need for a structured approach to conducting modelling studies, through which modellers (along with other team members) could think through different issues, from the physical aspects that need to be included in the model to outputs and applications required by the planners.

- The research performed herein attempts to address this problem by performing the academic research required to propose a Framework for Catchment Modelling Studies (FCMS) that presents *a staged and systematic approach to be used as a template for the development of modelling exercises to suit the physical characteristics of a basin and the level of detail required at each stage of a project, trying to strike a balance between project needs, cost and human resources.* The proposed FCMS parallels existing approaches for system-wide geomorphic studies, environmental assessments and engineering project management. In particular, one of the lessons learnt from the research studies is the need for a close relationship between geomorphic investigations and mathematical modelling.

- One of the major characteristics of the Rio Salado basin is the overriding importance of groundwater - surface water interaction in the flooding process. In particular, flooding in the Northwest region is initiated by groundwater exfiltration and, subsequently, by the control that geomorphic features (in the form of extensive longitudinal and parabolic dune fields) exert on surface water ponding and movement. Due to the absence of any natural surface water drainage network, water on the surface is not conveyed downstream by watercourses, resulting in prolonged and extensive flooding events. Figure 9.1 presents a view of Northwest region, its geomorphic features and its flooding patterns.

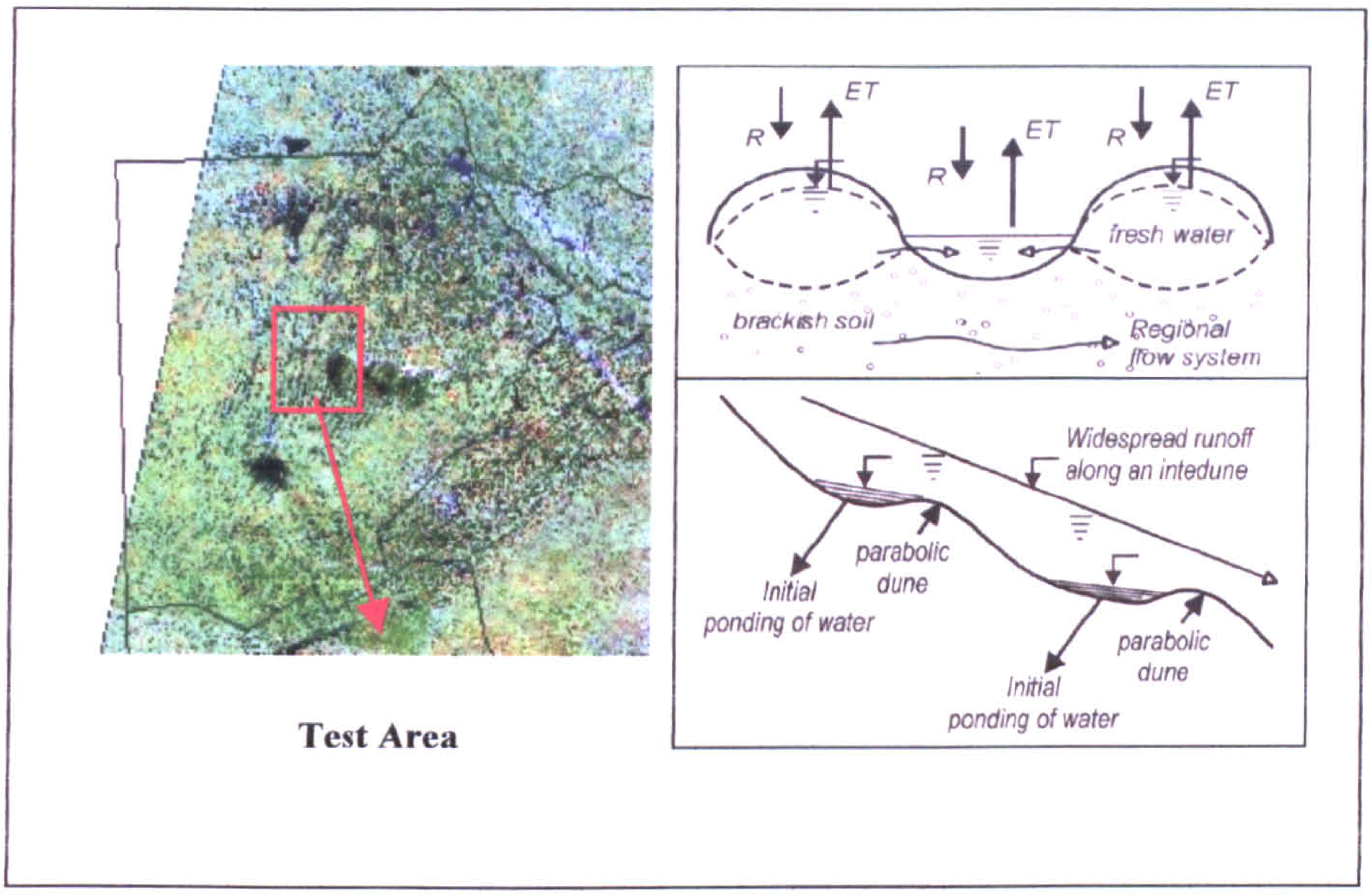


Figure 9.1: Northwest Region. Flooding and Conceptual Representation of GW-SW Interaction.

- Within the context of the FCMS approach, the flooding mechanism described above dictates that particular attention be given to GW-SW interaction. Consequently, technical research was focused on analysis of GW-SW interaction in a test area of the Northwest region, with the aim of exploring the basis for and advantages of coupled modelling. While the work was focused on the test area, the need to work in a manner consistent with the proposed FCMS required that frequent reference be made to the entire basin.

- In particular, analysis of SW-GW interaction and assessment of different approaches to its simulation centred on development of Flood Probability Maps (FPMs). An FPM is a spatial representation of the probability of occurrence of an event of a given magnitude or higher. A master plan study for catchment management must be supported by the analysis of the baseline situation (no project scenario) followed by comparative analysis of the set of measures (structural and non-structural) proposed for each area (with project scenario). In this context, FPMs are a key tool as they can be used to estimate affected areas for different return periods for each of the two scenarios. The areas benefiting under the 'with project' scenario provide the basis for integrated economic, social and environmental analysis of the proposed measures.

- A new program, iSISMOD, was developed with the aim of better simulating GW-SW interaction and, hence, generating improved FPMs. iSISMOD couples MODFLOW (McDonald and Harbaugh, 1988) with iSIS (HR Wallingford and Halcrow, 1995) to permit strong and dynamic coupling of groundwater and surface water systems. The key features of iSISMOD are:

(i) It couples two well known software packages preserving the full functionality of both programs and permitting to accommodate the different time steps inherent to groundwater and surface water systems, taking into account unstabilities issues that can arise from the different temporal resolutions.

(ii) A single control file was developed in ASCII format to gather the information required to performed a fully coupled run. The use of a control file preserves the structure of the data files used by the iSIS Flow and MODFLOW programs, while its structure was designed so that any MODFLOW available interface could be used to create most of it.

(iii) The program permits simulation of the interaction between a river or a reservoir and multiple aquifer cells. This is particularly valuable when modelling the interaction of an aquifer with a floodplain, taking into account the difference in driving heads that control leakage across the floodplain and the main river channel.

(iv) iSISMOD simulates the emergence of groundwater at the surface and its variation with time, leading to generation of variably contributing areas for surface runoff.

- Two different approaches for simulating groundwater-induced surface flooding and generating FPMs were compared. The first used MODFLOW alone and the second used iSISMOD. Mapping groundwater-induced surface flooding using MODFLOW is primarily the outcome of a simple comparison between the groundwater head and ground level for every grid cell. In contrast, iSISMOD predicts the extent, depth and duration of surface flooding using surface water heads instead of groundwater heads. Therefore, in iSISMOD flooding results from the dynamics of the water at the surface rather than the dynamics of the aquifer, as in the case when using MODFLOW alone.

- The research reported above provided the academic basis on which to address the technical questions framed in Chapter 4, as a prelude to addressing the more practical questions listed at the beginning of this chapter.

(i) *Do the individual modelling tools (HYSIM, MODFLOW and iSIS) on their own bear a reasonable degree of approximation for the simulation of the flooding mechanisms that drive the generation of hazards for the basin?*

Use of MODFLOW and iSIS in an uncoupled approach is suitable for the simulation of the groundwater and surface water systems provided that interaction between them is small. In this respect, a distinction should be made between the models as MODFLOW can account for weak interaction between a surface water system an its underlying aquifer (by use of either the RIVER or STREAM packages) while iSIS Flow cannot account for GW-SW interaction at all.

HYSIM possesses serious weaknesses in relation to its prime function within the modelling strategy adopted for the IMP studies, and these are most significant in the Northwest region of the Rio Salado basin. HYSIM cannot make good approximations of the aquifer recharge and surface runoff as it cannot simulate the relevant, key mechanisms in flatlands with shallow groundwater systems, such as: variation of infiltration, recharge and evapotranspiration from the saturated porous media as a function of water table position and dynamics of variably contributing areas to overland flow.

(ii) *How well does the groundwater model handle representation of surface water processes? Is it sufficient for answering the question flood/no flood?*

MODFLOW does not have the necessary modules to reproduce ponding of water along interdunal depressions and transfer of water once certain relief thresholds are exceeded surface water. These are the key processes responsible for flooding in the Northwest region of the Rio Salado basin.

Chapter 5 explained how, despite these limitations, MODFLOW was used in the IMP studies to answer the question flood/no flood. Provided the spatial resolution of the groundwater model matches the resolution of the relief, this approach can identify flooded areas with good degree of approximation for events with a low magnitude and a high frequency. However, it will be inaccurate for high magnitude, low frequency events because this approach cannot account for movement of water across the land surface once topographic thresholds are overtopped. The result is underestimation of the severity and extent of downstream flooding.

(iii) *The decoupled approach to calculate the FPMs is a direct consequence of the use of a modelling strategy that consisted of development of two separate, regional models. This was designed to suit the needs at a regional scale but would it still be applicable for areas where there is a potential overlap between processes?*

Chapter 4 explained the methodological approach to generating FPMs using separate regional models for groundwater and surface water. The approach resulted in separate estimations of flooding probability that were subsequently merged according to the higher frequency of occurrence of either fluvial or groundwater-induced surface flooding. A key feature of this approach is that for fluvial flooding the surface water model is used to analyse the impact of an event of a given frequency, whereas for groundwater flooding, the model is used to predict the responses of the system first, which are then subject to a frequency analysis.

A fully coupled approach for the estimation of FPMs implies that groundwater and surface water models are run on an homogeneous basis in terms of events: either on an event-basis or using a long-term series of hydrometeorological inputs. In practice, it would be possible to run the surface water model for a long-term series of input data, but it would not be advisable to run a groundwater model on an event basis due to its slow response, large inertia and large discrepancy between the frequency of the rainfall events and the associated frequency of flooding.

Using a decoupled approach for the generation of FPMs does not necessarily preclude using models that have strong GW-SW coupling, such as iSISMOD, which would be driven by the hydrometeorological data required by the aquifer component (i.e. MODFLOW).

The fluvial corridor of the Rio Salado is an area where there is a high potential overlap between fluvial and groundwater-induced flooding processes. Despite this, the main flooding process is fluvial flooding caused by the lack of conveyance capacity to convey flood flows in the existing drainage network, perhaps exacerbated by additional saturation overland flow. Flooding in the fluvial corridor could be simulated using iSISMOD while still maintaining an uncoupled approach to generating FPMs.

(iv) How sensitive are the FPMs to a combination of different scales for representing the groundwater flow system and the ground surface?

The generation of FPMs using MODFLOW alone turned out to be highly sensitive to the resolution of the uncoupled groundwater and ground surface models. Reducing the grid size in the MODFLOW improved correct identification of flooded areas. However, use of iSISMOD implies a different approach to dealing with spatial resolution. This program simulates the storage and movement of water at the surface. Hence, selection of the spatial resolution for the aquifer model can be partially decoupled from the issue of mapping flooded areas, as these are directly dependent on surface rather than groundwater heads. However, the appropriate spatial resolution should still be chosen with care in order to provide an adequate representation of the groundwater flow system. This leads to a distinction in terms of which groundwater flow system is being simulated. For a regional, baseline application (where the prime objective is identification of flooded areas) determination of regional groundwater heads should be sufficient and a large grid size can be used. For local and with-project applications, where a more detailed estimation of groundwater heads is required (i.e. around canals), simulation of the local groundwater system (between dunes) would dictate a smaller grid size.

(v) *Under what circumstances, the application of an integrated approach for fluvial and groundwater induced flooding be required? Would this be applicable at a regional scale?*

Based on the results of this research it may be concluded that there are circumstances under which using a fully coupled model like iSISMOD would be essential. A case in point is the Northwest area of the Salado basin, where a delicate interplay between hydrometeorological stresses, groundwater heads and geomorphic features is responsible for extensive and prolonged flooding. In modelling terms, coupling is required when heads in one system (GW) condition, and are conditioned by, the heads in the other system (SW).

Although the modelling philosophy presented in Chapter 8 is illustrated using iSISMOD in a template area, its application at a regional scale would still be feasible provided that a coarser spatial resolution were adopted for the aquifer model and the simulation of hydraulic aspects of the surface water component are simplified.

(vi) *Can MODFLOW alone serve the purpose of estimating the impact of the drainage scheme? Can an alternative approach be used?*

Based on analyses presented in Chapters 5 and 7 it can be concluded that use of MODFLOW alone to analyse the impact of a drainage scheme would suffer from all the limitations described in its use to generate baseline FPMs. In addition, a further problem is introduced because calculation of drainage rates (and hence channel capacity) is decoupled from analysis of the impact of surface drains on groundwater. While this approach could provide a sufficient approximation for the analysis of the functioning of drains during a flood event, it would be inadequate to assess the impact of the new drainage system during normal periods, in particular in relation to key environmental issues such as the impact on wetland areas and freshwater lenses.

An alternative approach would be to use iSISMOD for template areas, developing a fully coupled model that included the proposed drainage canals. This would allow designers to relate cross-sectional size and drainage density of the canals to their local impact, not only in terms reduction in flood extent and duration, but also in terms of lowering the water table.

- based on the analyses presented throughout the thesis and summarised above, it can be concluded that the modelling strategy adopted for the IMP study did have some significant limitations as far as reproducing observed flooding phenomena. In summary, flood predictions for the Northwest region of the Rio Salado basin, underestimated both the extent and frequency of inundation. Despite this, the potential benefits identified using the MODFLOW modelling approach adopted in the IMP were sufficient to suggest a set of structural measures that would be economically sustainable. In this respect, it could be argued that the modelling strategy, viewed within the context of the available economic and human resources, did fulfil the requirements of a prefeasibility project. However, the limitations identified through this research would rule out use of MODFLOW alone to perform the further analysis necessary to assess the functioning of the new drainage scheme during normal periods and its impact in the environmental and water resources equilibrium of this uniquely important region. This would definitely preclude its use in the feasibility and engineering design studies that would precede construction and implementation of any flood management scheme.

- Finally, it can also be concluded that the adoption of an FCMS, such as that proposed in Chapter 8, would have added significant value to the IMP studies by allowing the multi-disciplinary team to think the technical issues through more systematically resulting in improved problem identification and adoption of necessary modifications and developments at an early stage of the project. To demonstrate clearly the potential value added by an FCMS, Tables 9.1 and 9.2 present a summary of the modelling strategy adopted in the IMP studies and a modified approach that could have resulted in a more robust set of results. The most significant conclusion is that the new approach would have allowed a more accurate assessment of the complete modelling cycle, leading to more efficient development of a more sustainable integrated catchment management plan (Figure 9.2).

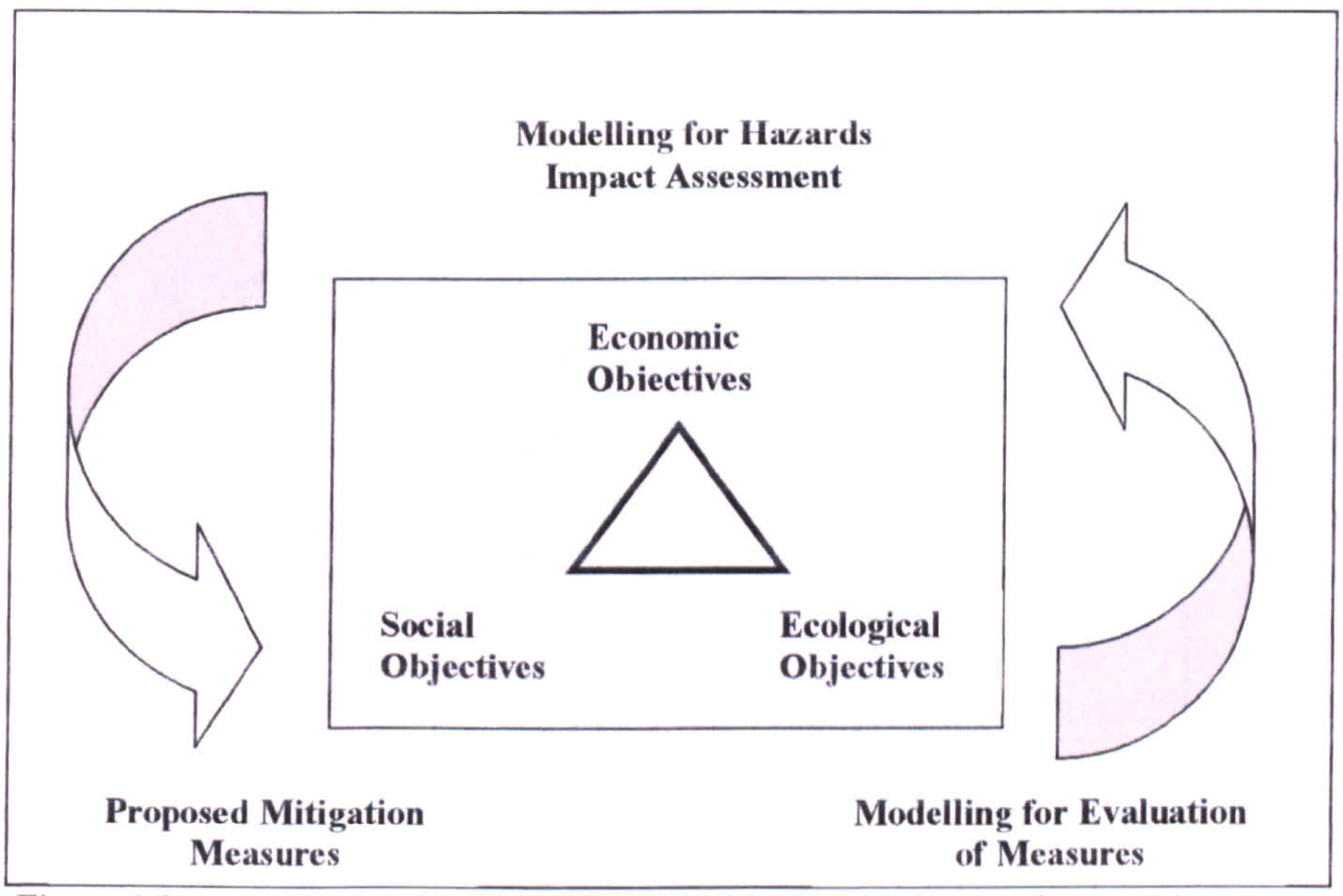


Figure 9.2: The Modelling & Sustainability Cycle for Catchment Management Plans.

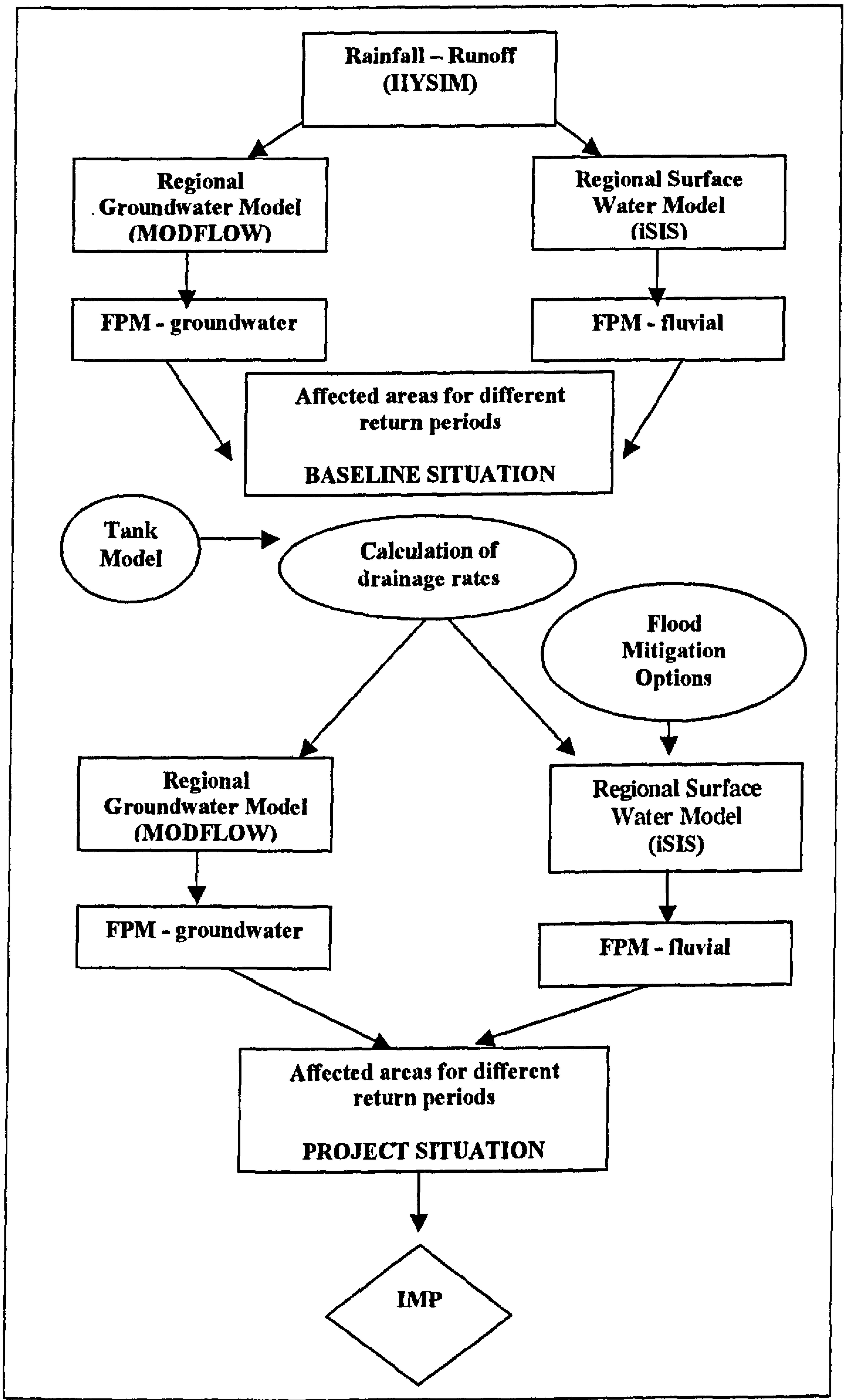


Table 9.1: Summary of Modelling Strategy adopted in the IMP Studies.

INITIAL CONCEPTUALIZATION	
Two risk models are identified: **1. Fluvial flooding** This model concentrates along the fluvial corridors involving an area of approximately 10,000km^2 **2. Groundwater flooding** This model concentrates in the Northwest region and, to a lesser extent, in the Zona Deprimida, occupying in total the majority of the basin area. Total area of the Rio Salado basin is: 170,000km^2.	
Primary modelling theme **GW and SW interaction**	**Secondary modelling theme** **Fluvial and canal network**
BASELINE SCOPING MODEL	
Build MODFLOW model to characterise the regional groundwater flow system. Include key watercourses in MODFLOW to make a broad assessment of GW-SW interaction as a contribution to the regional balance	Statistical analysis of peak river flows in order to characterise the problem of fluvial flooding. Analysis of low flows in rivers to assess the contribution from the underlying aquifer.
Regional and Sub regional water balances	

REGIONAL OPERATIONAL MODELLING	
Option A Development of a regional iSISMOD model using large flood cells to represent surface processes.	Development of a rainfall runoff model (i.e. HYSIM) to provide input to the surface water model (iSIS) Development of a 1D surface water model (iSIS)
Option B Development of a set of sub-regional iSISMOD models (at higher resolution than the above). The selection of areas for models should follow geomorphic sub-regions.	

FPM - groundwater

FPM - fluvial

Affected areas for different return periods

BASELINE SITUATION

LOCAL MODELLING	
Baseline Situation A Test Area model could be set up in the dune area to assess GW-SW interaction before developing the regional or set of sub-regional iSISMOD models in the Operational Modelling Block. **Project Situation** Sub-regional iSISMOD models used to test drainage schemes. This will lead to the calculation of drainage rates for different return periods	**Baseline Situation** Sub-regional iSISMOD model to test GW-SW interaction in the fluvial corridor. This would be basically applied to analysis of the impact of saturation overland flow in the prediction of flood extent by the 1D model.
Calculation of drainage rates	

CATCHMENT MODELLING	
Option A1 In this option, the regional iSISMOD model will be modified to test the regional impact of the drainage schemes. The effect of the drains could be simulated using flow time boundaries (or logical abstraction units) attached to each flood cell. Each flow time boundary will be derived from the drainage rates calculated previously using iSISMOD.	The operational model is used to test the impact of proposed drainage schemes along the fluvial corridors. The drainage rates calculated using iSISMOD will be transformed as flow time boundaries for iSIS.
Option A2 Modifying the infiltration time series that enters the models is also an option - but this has the disadvantage of assuming the functioning of the drains.	
Option B In this option the impact of each drainage system would be analysed by modelling it explicitly in each sub-model (hence, in each sub-region)	

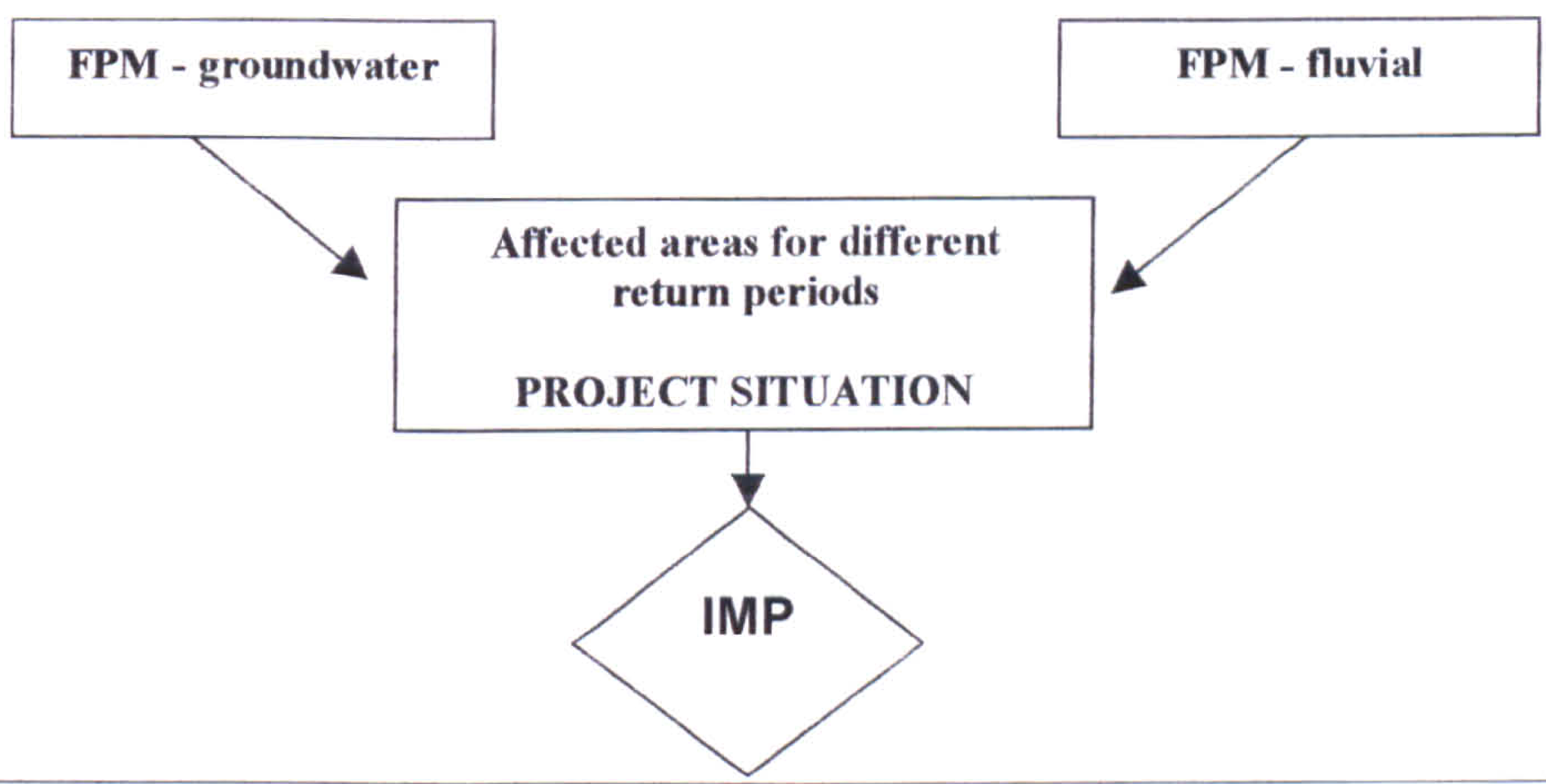


Table 9.2: Potential application of the proposed FCMS to the IMP studies.

9.3 Recommendations

Recommendations for further research are structured in two sections, in a manner consistent with main and technical sub-topic of the thesis: the FCMS and iSISMOD.

9.3.1 Recommendations for the FCMS

- The FCMS proposed in this thesis should be exposed to discussion and critique by different communities of experts: primarily specialists in the fields of geomorphology, environmental studies, engineering design and also economy, in order to deepen the section dealing with *matching modelling needs to catchment management plans.* In particular, the views of specialists should allow refinement of concepts governing how models can be used to provide support to the different disciplines. This would help to focus the development of models capable of producing a wider spectrum of deliverables and supporting a greater range of practical applications.

- The utility of the FCMS can only be enhanced through the addition of more practical examples to illustrate and accompany the approach put forward here. Utility could be improved initially by performing a sensitivity analysis on the different models used in the IMP studies and the research reported here, at both regional and local scales. Some of the exercises that could be carried out to good effect are summarised in Table 9.3:

Modelling Exercise	Purpose
Set up an iSISMOD model for a template area along the fluvial corridor of the Rio Salado.	Analyse the impact of groundwater flooding and saturation overland flow in the prediction of fluvial flooding.
Use the Test Area model to simulate the functioning of drainage canals.	Assess the prediction of drainage rates. Construction of charts to link: drainage density, sizes and spacing, return period, areas recovered for exploitation and environmental impact.
Test iSISMOD at a regional scale.	Assess feasibility of its application at an operational and regional level. Spatial and temporal resolutions required. Level of simplification required in terms of the simulation of GW and SW interaction.
Test the functioning of iSISMOD for different schematic configurations to simulate the functioning of the surface water system.	Assess speed of model building, convenience, accuracy, speed of execution and flexibility of each type of schematisation. In particular for the test area, confront the use of river sections and flood cells.
Test iSISMOD under different spatial resolutions of the aquifer model.	Assess the impact on the generation of FPMs and on the analysis of the drainage canals.
Test iSISMOD and the full functioning of the variably contributing area to saturation overland flow.	Refine the analysis of the generation of FPMs.

Table 9.3: Proposed modelling exercises

- The FCMS would also benefit from experience gained and examples generated through its application to other hydrological phenomena where GW-SW interaction is important, such as the case of flood attenuation due to bank storage effects, analysis of low flows in rivers, wetland management and irrigation within river corridors.

- A potentially important further extension of the FCMS would be to relate it to other vital aspects of catchment modelling, such as water quality and sediment transport.

- A flow chart or decision tree should be added to the FCMS, linking the requirements of catchment studies, modelling deliverables, hydrological issues, and model development. This would help users to decide which modelling component to use at each stage of the project.

- Finally, it would be extremely useful to use the proposed FCMS in an integrated study of a large basin other than that of the Rio Salado.

9.3.2 Recommendations for improving iSISMOD

The aspects of iSISMOD that could most immediately be enhanced by further research are summarised in Table 9.4.

Development	Potential Benefit / Application
Finalize the implementation of the variably contributing area option within the latest version of iSISMOD. This was done in previous versions.	This allow the user to assess in more detail the dynamics of flooding, improving the FPMs obtained in Chapter 7.
Include an option to use the wetted perimeter (instead of the top width) to represent interaction between the SW and the GW systems.	Some studies may require a more detailed representation of the streambed surface. For example, for evaluation of wetlands and floodplain interaction with the underlying aquifer.
Allow the variation of the streambed leakage (kv) with time, to simulate reduction of conductance with time due to sediment deposition.	This option would also improve representation of the dynamics of surface flooding, permitting the model to simulate the duration of flooding more accurately.

Table 9.4: Recommended developments for iSISMOD

Allow other iSIS Flow units, such as those that solve the propagation of a flood wave using the Variable Parameter Muskingum Cunge method, to interact with MODFLOW.	This option would be useful to expand the utility of the program in more regional and long-term applications when a full hydrodynamic solution is not required.
Investigate the practical possibility of using the adaptive time step method (currently available in normal iSIS Flow simulations) for coupled runs.	This facility would permit the model to run faster simulations as the adaptive time step option automatically varyies the time step to suit convergence requirements at specific moments during a simulation.
Improve construction of the control file that maps the aquifer cells that interact with each river or reservoir node.	At present construction of the iSISMOD control file is carried out manually by determining which MODFLOW cells will interact with iSIS. An option could be developed in the model to automatically construct this control file. This would be particularly useful when adding extra nodes in the schematisation of iSIS. This option could be developed within the current GIS (ArcView) interface of iSIS.
Investigate the functioning of iSISMOD when the cell re-saturation option (drying and rewetting) of MODFLOW is operational.	The computational aspects of iSISMOD should not be altered if the rewetting option of MODFLOW is used. However, it should be checked that iSISMOD reads groundwater heads after a cell rewets. The rewetting option could be used if a detailed vertical representation of the underlying aquifer is required.

Table 9.4: cont.

REFERENCES

Abbot, M.B., Bathurst, J.C., Cunge, J.A., O'Connell, P.E. and Rasmussen, J., (1986). An introduction to the European Hydrological System, "SHE", 1. History and Philosophy of a physically-based, distributed modelling system. *Journal of Hydrology*, 87: 45-49.

Abbot, M.B., Bathurst, J.C., Cunge, J.A., O'Connell, P.E. and Rasmussen, J., (1986). An introduction to the European Hydrological System, "SHE", 2. Structure of a physically-based, distributed modelling system. *Journal of Hydrology*, 87: 61-77.

Acreman M. and Adams, B. (1999). *Low Flows, Groundwater and Wetland Interactions*. Institute of Hydrology.

Agua y Energia Electrica (AEE). (1990). Plan de Manejo de los Excedentes Hidricos del Noroeste de la Provincia de Buenos Aires. *(Flood management plan for the Northwest area of Buenos Aires* - Report on mathematical modelling of the north-west area).

Ameghino, F (1886). *Las Inundaciones y las Secas en la Provincia de Buenos Aires*. Obras de retención y no de obras de desagüe. (*Floods and Drought in Buenos Aires. Retention works as opposed to drainage works*).

Anderson, M.G. and Burt, T.P. (1990). Process studies in hillslope hydrology: an overview. In: Anderson, M.G. and Burt, T.P. (eds.) *Process Studies in Hillslope Hydrology*. John Wiley and Sons Ltd. Chichester. England.

Anderson, M.G. and Burt, T.P. (1990). Subsurface Runoff. In: Anderson, M.G. and Burt, T.P. (eds.) *Process Studies in Hillslope Hydrology*. John Wiley and Sons Ltd. Chichester. England.

Anderson, M.G. and Bates, P.D. (2001). Hydrology Science: Model Credibility and Scientific Integrity. In: Anderson, M.G. and Bates, P.D. (eds.) *Model Validation: Perspectives in Hydrological Science.* John Wiley and Sons Ltd. Chichester. England.

Arnold, J.G. and Williams, J.R. (1995). SWRRB. A Watershed Scale Model for Soil and Water Resources Management. In: Singh, V.P. (1995) (ed.) *Computer Models of Watershed Hydrology*. Water Resources Publications.

Arnold, J.G., Allen, P.M. and Bernhardt, G. (1992). A Comprehensive Surface-Groundwater Flow Model. In: *Journal of Hydrology,* 142 (1993), pp.47-69.

Auge, M.P. and Hernandez, M.A. (1983). Caracteristicas geohidrologicas de un aquifero semiconfinado en la Llanura Bonaerense. (Hydrogeological features of a semiconfined aquifer in the Buenos Aires plain). In: *Hydrology on Large Fatlands, Proceedings of the Olavarria Simposium*. Vol. II, April 1983. UNESCO, República Argentina.

Banta, E.R. (2000). MODFLOW-2000, *The US Geological Survey Modular Ground-Water Model – Documentation of Packages for Simulating Evapotransporation with a Segmented Function (ETS1) and Drains with Return Flow (DRT1). US Geological Survey.* Open-file Report 00-466. Denver, Colorado 2000.

Bates, P.D and De Roo, A.P.J. (2000). A simple raster-based model for floodplain inundation. *Journal of Hydrology* 236, 54-77.

Beven, K. (1989). Changing ideas in hydrology – the case of physically-based models. *Journal of Hydrology* 105: 157-172.

Beven, K. and Wood, E.F. (1983). Catchment geomorphology and the dynamics of runoff contributing areas. *Journal of Hydrology* 39, 139-158.

Beven, K., Lamb, R., Quinn, P., Romanowicks, R. and Freer, J. (1995) TOPMODEL. in: Singh, V.P. (1995) (ed.) *Computer Models of Watershed Hydrology*. Water Resources Publications.

Beven, K. (2001) Calibration, Validation and Equifinality in Hydrological Modelling: A Continuing Discussion ... In: Anderson, M.G. and Bates, P.D. (eds.) *Model Validation: Perspectives in Hydrological Science*. John Wiley and Sons Ltd. Chichester. England.

Bowles, D.S. and O'Connel, P.E. (ed) (1991). Proceedings of the NATO Advanced Study Institute on Recent Advances in the Modelling of Hydrologic Systems. Sintra, Portugal, 1988. Kuwler Academic Publishers, 1991.

Bradley, C. (1996). Transient modelling of water-table variation in a floodplain wetland, Narborough Bog, Leicestershire. *Journal of Hydrology* 185 (1996) 87-114. Elsevier.

Carter, V. (1983). Wetland Hydrology in the United States. In: *Hydrology on Large Fatlands, Proceedings of the Olavarria Simposium*. Vol. II, April 1983. UNESCO, República Argentina.

Cheng, X. and Anderson, M.P. (1993). Numerical Simulation of Groundwater Interaction with Lakes Allowing for fluctuating Lake Levels. *Groundwater,* Vol.31 No.6.

Chorley, R.J. (ed.) (1969). *Water, Earth and Man.* Methuen, London, 1969.

Consejo Federal de Inversiones (CFI).1980. *Estudio de la Zona Deprimida del Salado. Estudios Geologicos,* Vol 3, Part B. *(Study of the Río Salado Plain zone).*

Convenio Ministerio de Obras y Servicios Publicas (MOSP). 1987. *Lineamientos Generales y Regionales para un Plan Maestro de Ordenamiento Hidrico del Territorio. (Regional Guidelines for the development of a Master Plan).*

David, P. (2001). ISGW – The Integrated Hydrologic Model Coupling HSPF and MODFLOW. In: Panigrahi, B.K. (2001). *Integrated Surface and Ground Water Management,* EWRI, ASCE.

Donigian, A.S. Bricknell, B.R. and Imhoff, J.C. (1995). Hydrological Simulation Program – Fortran (HSPF). In: Singh, V.P. (1995) (ed.) *Computer Models of Watershed Hydrology.* Water Resources Publications.

Leopold, L.B. and Dunne, T. (1978). *Water in Environmental Planning,* EEUU, Freeman, 1978.

Dunne, T., Moore, T.R. and Taylor, C.H. (1975) Recognition and prediction of runoff-producing zones in humid regions. *Hydrological Sciences Bulletin,* XX, 3. 9/1975.

DYMAS. (1974). *Contribución al Mapa Hidrogeológico de la Provincia de Buenos Aires.* Escala 1:500,000 Zonas Noroeste. *(Contribution to the Buenos Aires Province hydrogeological map).*

European Union (2000). *Water Framework Directory.*

Ewen, J., Parkin, G. and O'Connell, E. (1999). SHETRAN: a Coupled Surface/Subsurface Modelling System for 3D Water Flow and Sediment and Solute Transport in River Basins. *Journal of Hydrologic Engineering,* 1999.

Feldman, A.D. (1995). HEC-1 Flood Hydrograph Package. In: Singh, V.P. (1995) (ed.) *Computer Models of Watershed Hydrology.* Water Resources Publications.

Fidalgo, F. (1983). Algunas caracteristicas de los sedimentos superficiales en la cuenca del Rio Salado y en la Pampa Ondulada. *(Some features of the surface sediments in the Salado Cathment)* In: *Hydrology on Large Fatlands, Proceedings of the Olavarría Simposium.* Vol. II, April 1983. UNESCO, República Argentina.

Gardiner, J. (1994) What the Client needs? Environmental modelling in the Hydrological Cycle. *Journal of the Chartered Institution of Water and Environmental Management (CIWEM)* 11, April, 1997.

Gardiner, J.L. (1991). *Rivers Projects and Conservation. A Manual for Holistic Appraisal.* Wiley, 1991.

Grayson, R.B., Moore, I.D. and McMahon, T.A. (1992). Physically-based hydrologic modelling. Is the concept realistic? *Water Resources Research* 26: 2659-2666.

Halcrow and Wallingford. (1995). *ISIS Flow. User Manual.*

Halcrow Group Ltd. (1999) *Integrated Master Plan for the Salado River Basin. Ministry of Public Works.* Buenos Aires. Argentina. Main Volume and 22 Annexes.

Hollis, G.E. and Acreman, M. (1994). The Functions of Wetlands within Integrated River Basin Development: International Perspectives. In: Kirby, C. And White, W.R. (eds.).1994. *Integrated River Basin Development*, John Wiley and Sons.

HR Wallingford (2002). *State of the Art Review, Work Package 1. IT Frameworks (Harmon IT)*. Contract EVK1-CT-2002-00090. Report SR 598.

HR Wallingford (2001). *Risk, Performance and Uncertainty in Flood and Coastal Defence. A review*. Volume 1. First Draft. Report SR587. September 2001.

IATASA (1994). *Plan Director para la Cuenca de las Lagunas Encadenadas del Oeste y A° Vallimanca. (Master Plan for the Western Lakes and Vallimanca River catchments)*. Ministry of Public Works, 1994.

INDEC (1991). *Censo Nacional de Población y Vivienda 1991*. (*National Census 1991*)

Jobson, H.E. and Harbaugh, A.W. (1999). *Modifications to the Diffusion Analogy Surface-Water Flow Model (DAFLOW) for Coupling to the Modular Finite-Difference Ground-Water Flow Model (MODFLOW)*. U.S. Geological Survey, Open-file Report 99-217.

Loáciga, H.A. (2001). Ground-Water/Surface-Water Interactions in a Karst Aquifer. In: Panigrahi, B.K. (2001). *Integrated Surface and Ground Water Management*, EWRI, ASCE.

Malagnino,E.C. (1988). Evolucion del sistema fluvial de la Provincia de Buenos Aires desde el Pleistoceno hasta la Actualidad. (Evolution of the fluvial system in the Buenos Aires province from the Pleistoceno to date) *Proceedings of the Geological Congress in Buenos Aires*, Bahia Blanca, ACTAS, 201-211.

Manley, R. (1993). *HYSIM. User Guide and Reference Manual.*

McDonald, M.G. and Harbourgh, A.W. (1988). *A modular three dimensional finite difference ground water flow model.* US Geological Survey, Open file report 83-875.

Mc Vicar, T.K., VanLent, T. and Castro, A. (1983). *South Florida Water Management Model. Documentation Report.* Resource Planning Department. South Florida Water Management District. Technical Publication 84-3. December 1983.

Merrit, M.L. and Konikov, L.F. (2000). *Documentation of a Computer Program to Simulate Lake-Aquifer Interaction Using the MODFLOW Ground-Water Flow Model and the MOC3D Solute-Transport Model.* U.S. Geological Survey, Water Resources Investigations Report 00-4167.

Mitchel, B. (1989). Integrated Water Management. In: Mitchel, B. (ed.) *Integrated Water Management: International Experiences and Perspectives.* Belhaven Press, 1989.

Morel-Seytoux, H.J. (2001). Groundwater. In: Anderson, M.G. and Bates, P.D. (eds.) *Model Validation: Perspectives in Hydrological Science.* John Wiley and Sons Ltd. Chichester. England.

Morita, M and Yen, B.C. (2002). Modelling of Conjunctive Two-Dimensional Surface-Three-Dimensional Subsurface Flows. *Journal of Hydraulic Engineering*, Vol. 128, No.2, February 2002.

Mortellaro, S., Krupa, S., Fink, L. and VanArman, J. (1995). *Literature Review on the Effects of Groundwater Drawdowns on Isolated Wetlands.* Technical Publication 96-01. South Florida Water Management District, West

Mull, R. (1983). Net Recharge in Shallow Groundwater Systems. In: *Hydrology on Large Fatlands, Proceedings of the Olavarria Simposium.* Vol. II, April 1983. UNESCO, República Argentina.

Nawalany, M., Recking, A. and Reeve, C. (1994). Representation of river-aquifer interactions in regional groundwater models. In: Reeve and Watts (eds) (1994), *Groundwater – Drought, Pollution & Management.* 1994, Balkema, Rotterdam.

Newson, M. (1994). Sustainable Integrated Development and The Basin Sediment System: Guidance from Fluvial Geomorphology. In: Kirby, C. (1994). *Integrated River Basin Development.*

Newson, M. (1997). Land and Water: Interactions. In: Newson, M. (1997). *Land, Water and Development,* Routledge, London.

Newson, M. (1997). Preface to 1st Edition, Prologue and Natural River Basins, Transfer Systems. In: Newson, M. (1997). *Land, Water and Development,* Routledge, London.

Newson, M. (1997). Technical Issues in River Basin Management. In: Newson, M. (1997). *Land, Water and Development,* Routledge, London.

O'Loughin, E.M. (1986). Prediction of surface saturation zones in natural catchments by topographic analysis. *Water Resources Research.* 22(5): 794-804.

Ostfeld, A. Muzaffar, E. and Lansley, K.E. (1999). Analytical Ground-Water Flow Solutions for Channel-Aquifer Interaction. *Journal of Irrigation and Drainage Engineering*, Vol. 125, No.4. July/August 1999.

Paoli, C. and Giacosa, R. (1983). Necesidades de Investigaciones Hidrológicas en áreas de Llanura. In: *Hydrology on Large Flatlands, Proceedings of the Olavarría Simposium*. Vol. II, April 1983. UNESCO, República Argentina.

Parkin, G. and Adams, R. (1998). Using catchment models for groundwater problems: evaluating the impacts of mine dewatering and groundwater abstraction. In: *Hydrology in a Changing Environment*. Volume II, 1998, British Hydrological Society.

Pedraza, R., Ceirano, E., Ercole, C. and Mitri, A. (1992). Aplicación de un modelo matemático hidrológico-hidráulico al Complejo Lagunar El Hinojo-Las Tunas (Application of a hydrologic and hydraulic model to the Hinojo-Las Tunas Lakes). *Proceedings of the XV Latinamerican Congress of Hydraulics*. Cartagena. Colombia.

Perkins. S.P. and Koussis, A.D. (1996). Stream-Aquifer Interaction Model with Diffusive Wave Routing. *Journal of Hydraulic Engineering*, Vo. 122, No.4, April 1996.

Pinder, G.F. and Sauer, S.P. (1971). Numerical Simulation of Flood Wave Modification due to Bank Storage Effects. *Water Resources Research*. Vol. 2, No.1. (February 1971).

Prudic, D.E. (1989). *Documentation of a Computer Program o Simulate Stream-Aquifer Relations*. Open File. Rep. 88-729. US Geological Survey, Denver, Colorado.

Refsgaard, J.C. and Storm, B. (1995). Mike She. in: Singh, V.P. (1995) (ed.) *Computer Models of Watershed Hydrology*. Water Resources Publications.

Restrepo, J.I., Montoya, A.M. and Obeysekera, J. (1998). A Wetland Simulation Module for the MODFLOW Groundwater Model. *GROUND WATER*, Vol. 36, No. 5, September-October 1998.

Rodriguez, L.B., Pavese, J. and Vionnet, C. (1998). The effects of excess irrigation on the water table fluctuations in the Neuquen River Valley, Argentina. In: *Hydrology in a Changing Environment.* Volume II. British Hydrological Society.

Sacks, L.A., Herman, J.S., Konikov, L.F. and Vela, A.L. (1991). Seasonal dynamics of groundwater-lake interactions at Doñona National Park, Spain. *Journal of Hydrology* 136 (1992), pp. 123-154, Elsevier, Amsterdam.

Secretary of National Resources and Sustainable Development, Argentina (1971). *Convention on Wetlands*, Ramsar, Irán 1971.

Serageldin, Ismael (1995). Making Development Sustainable. In: Serageldin and Steer (eds.) *Making Development Sustainable*, Environmentally Sustainable Development Series Titles. Ocassional paper Series No. 2, World Bank.

Shedlock, R.J., Wilcox, D.A., Thompson, T.A. and Cohen, D.A. (1993). Interactions between ground water and wetlands, southern shore of Lake Michigan, USA. *Journal of Hydrology* 141 (1993) 127-155. Elsevier, Amsterdam.

Soar, P.J. and Thorne, C.R. (2001). *Channel Restoration Design for Meandering Rivers*. Coastal and Hydraulics Laboratory. US Army Corps of Engineers. ERDC/CHL. CR–01-1.

Swain, E.D. (1994). Implementation and Use of Direct-Flow Connection in a Coupled Groundwater and Surface Water Model. In: *Groundwater*, Vol.32, No.1, Jan-Feb. 1994.

The Institution of Civil Engineers (2001). *Learning to Live with Rivers*. Final Report of the Institution of Civil Engineers's Presidential Commission to Review the Technical Aspects of Flood Risk Management in England and Wales, Institution of Civil Engineers, London.

Thorne, C.R., Hey, R.D. and Newson, M.D. (1997). *Applied Fluvial Geomorphology for River Engineering and Management*. John Wiley and Sons Ltd. Chichester, UK.

Thorne, C R (1998) *Stream Reconnaissance Guidebook: Geomorphological Investigation and Analysis of River Channels*, J Wiley and Sons, Chichester, UK, 127p.

Wasantha Lal. A.M. (2001). Modification of Canal Flow due to Stream-Aquifer Interaction. *Journal of Hydraulic Engineering*, Vol. 127, No.7, July 2001.

Environment Agency (2003). *Water Resources Planning Guideline*, Version 3.3 December 2003.

Wolman, M.G and Miller, J.P. (1960). Magnitude and Frequency of Forces in Geomorphic Processes. *Journal of Geology* 68: 54-74.

World Bank (1991). *Operational Directive 4.01 on Environmental Assessment*. The World Bank Operational Manual.

Wyness, A.J., Rippon, P.W. and Wardlaw, R.B. (1994). Application of an integrated model to chalk catchments. In: Reeve and Watts (eds) (1994), *Groundwater – Drought, Pollution & Management.* 1994, Balkema, Rotterdam.

Yan, J. and Smith, K.R. (1994). Simulation of Integrated Surface Water and Ground Water Systems – Model Formulation. *Water Resources Bulletin,* American Water Resources Association, Vol. 30, No.5, October 1994.

Yrigoyen,M.R. (1973). *Geologia del subsuelo y plataforma continental. (Geology of the subsoil and continental platform).* National Geological Congress, Buenos Aires, 139-168.

Zambrano,J.J. (1974). Cuencas sedimentarias en el subsuelo de la Provincia de Buenos Aires y zonas adyacentes. (Sedimentary catchments in the subsoil of Buenos Aires and adjacent zones). *Magazine of the Argentinean Geological Association* 29, 4, 443-469.

Zevenbergen, L.W. and Thorne, C.R. (1986). Quantitative analysis of land surface topography. In: *Earth Surface Process and Landforms.* Vol.12, 47-56 (1987).

BIBLIOGRAPHY

Anderson, M.G., Walling, D.E. and Bates, P.D. (1996). *Floodplain Processes.* John Wiley and Sons Ltd., Chichester, England.

Anderson, M.P. and Woessner, W.W. (1992). *Applied Groundwater Modeling. Simulation of Flow and Advective Transport.* Academic Press.

Anderson, M.P. Groundwater Modelling in the 21st Century. In: El-Kady, A.I. *Groundwater Models for Resources Analysis and Management.* Lewis Publishers.

Arnell, N. (1996). *Global Warning, River Flows and Water Resources.*

Arnold, J.G., Allen, P.M. and Bernhardt, G. (1992). A Comprehensive Surface-Groundwater Flow Model. In: *Journal of Hydrology,* 142 (1993), pp.47-69.

Bear, J. (1979). *Hydraulics of Groundwater.* Mc Graw-Hill Inc. 1979.

Becker, A. and Braun, P. (1999). Disaggregation, aggregation and spatial scaling in hydrological modelling. *Journal of Hydrology* 217 (1999) 239-252.

Beven, K. (1985). Distributed Models. In: Anderson, M.G. and Burt, T.P. (1985) *Hydrological Forecasting,* John Wiley and Sons. Ltd.

Beven, K.J. and Kirkby, M.J. (1979). A physically based, variable contributing area model of basin hydrology. *Hydrological Sciences* – Bulletin. 24, 1,1979.

Bloschl, G. and Sivapalan, M. (1995). Scale issues in Hydrological Modelling: A Review. *Hydrological Processes – An International Journal*, volume 9, 1995.

Bowles, D.S. and O'Connel, P.E. (ed) (1991). *Proceedings of the NATO Advanced Study Institute on Recent Advances in the Modelling of Hydrologic Systems.* Sintra, Portugal, 1988. Kuwler Academic Publishers, 1991.

Brion, L., Tarboton, K., Santee, E., Cadavid, L., Trimble, P. and Obeysekera, J. (2001). South Florida Water Management Model: Regional-Scale Water Management Tool. In: Panigrahi, B.K. (2001). *Integrated Surface and Ground Water Management*, EWRI, ASCE.

Burke, J.J., Jones, M.J. and Kasimona, V. (1994). Approaches to Integrated Water Resources Development and Management of the Kafue Basin, Zambia. In: Kirby, C. (1994). *Integrated River Basin Development.*

Burke, S., Mulligan, M. and Thornes, J.B. (1998). Key parameters controlling recharge at a catchment scale. In: *Hydrology in a changing environment.* Volume II. British Hydrological Society.

Carter, V. (1983). Wetland Hydrology in the United States. In: *Hydrology on Large Fatlands*, Proceedings of the Olavarría Simposium. Vol. II, April 1983. UNESCO, República Argentina.

Charnock, T.W., Hedges, P.D. and Elgy, J. (1996) Linking multiple process level models with GIS. In: *HYDROGIS 96.* Proceedings of the Vienna Conference, April 1996.

Chiew, F.H.S. and Mc Mahon, T.A. (1990) Estimating groundwater recharge using a surface watershed modelling approach. *Journal of Hydrology*, 114 (1990) 285-304.

Chow, V.T., Maidment, D.R. and Mays, L.W. (1994). Hydrological Processes. In: Chow et al. (1994). *Applied Hydrology.*

Christensen, S., Rasmussen, K.R. and Moller, K. (1998). Prediction of Regional Groundwater Flow to Streams. *Groundwater,* Vol.36, No.2, March-April 1998.

Crebas, J.I., Gilding, B.H. and Wesseling, J.W. (1984). Coupling of Groundwater and Open-Channel Flow. *Journal of Hydrology* 72 (1984) 307-330. Elsevier, Amsterdam.

Cunningham, A.B. and Sinclair, P.J. (1979). Application and Analysis of a Coupled Surface and Groundwater Model. *Journal of Hydrology* 43 (1979) 129-148. Elsevier, Amsterdam.

De Vries, J.J. (1995). Seasonal expansion and contraction of stream networks in shallow groundwater systems. *Journal of Hydrology* 170 (1995), pp. 15-26, Elsevier.

De Vries, J.J.(1993). Dynamics of the interface between streams and groundwater systems in lowland areas, with reference to stream net evolution. *Journal of Hydrology* 155 (1994), pp. 39-56, Elsevier.

Dury, G.H. (1969). Relation of Morphometry to runoff Frequency. In: Chorley, R.J. (ed.). *Water, Earth and Man.* London, Methuen.

Eddy, J.A. (1993). Environmental Research: What We Must Do. In: Godchild, M. Et al. (eds.) *Environmental Modelling with GIS,* Oxford, Oxford University Press.

Ernst, L.F. (1978). Drainage of undulating sandy soils with high groundwater tables. *Journal of Hydrology* 39 (1978), pp. 1-30, Elsevier, Amstredam.

Fedra, K. (1993) GIS and Environmental Modelling. In: Goodchild, M., Parks, B.O. and Steyaert, L.T. (eds.) (1993). *Environmental Modelling with GIS*, Oxford, Oxford University Press.

Franchini, M., Wendling, J., Obled, C. and Todini, E. (1996). Physical interpretation and sensitivity analysis of the TOPMODEL. *Journal of Hydrology* 175, 293-338.

Hashmi, M.A. and Garcia. L.A. (1998). Spatial and Temporal Errors in estimating regional evapotranspiration. *Journal of Irrigation and Drainage Engineering*, Vol. 124, No. 2.

Health and Safety Executive (1999). *Reducing Risks, Protecting People.* Risk Assessment Policy Unit, London.

Hill, B.M. (1996). Use of Numerical Model for Management of Shaloww Groundwater Levels in the Yuma, Arizona Area. In: *Groundwater*, Vol.34, No.3, May-June 1996.

Kaleris, V. (1998). Quantifying the exchange rate between groundwater and small streams. *Journal of Hydraulic Research*, Vol. 36, 1998, No.6.

Kirby, M.J. (1969). Infiltration, Throughflow and Overland Flow. In: Chorley, R.J. (ed.). *Water, Earth and Man.* London, Methuen.

Kirkby, M.J. (1985). Hillslope Hydrology. In: Anderson, M.G. and Burt, T.P. (ed) *Hydrological Forecasting.* John Wiley and Sons Ltd., 1985.

Klemes, V. (1986). Dilettantism in Hydrology: Transition or Destiny? *Water Resources Research*, Vol. 22, No.9, pages 177s-188s.

Leopold, L.B. and Dunne, T. (1978). Drainage Basin. In: Leopold, L.B. and Dunne, T. *Water in Environmental Planning*, EEUU, Freeman.

Leopold, L.B. and Dunne, T. (1978). Groundwater. In: Leopold, L.B. and Dunne, T. Water in Environmental Planning, EEUU, Freeman.

Leopold, L.B. and Dunne, T. (1978). Precipitation. In: Leopold, L.B. and Dunne, T. *Water in Environmental Planning*, EEUU, Freeman.

Leopold, L.B. and Dunne, T. (1978). River Channels. In: Leopold, L.B. and Dunne, T. Water in Environmental Planning, EEUU, Freeman.

Leopold, L.B. and Dunne, T. (1978). Runoff Processes. In: Leopold, L.B. and Dunne, T. *Water in Environmental Planning*, EEUU, Freeman.

Leopold, L.B. and Dunne, T. (1978). The Water Balance. In: Leopold, L.B. and Dunne, T. *Water in Environmental Planning*, EEUU, Freeman.

Leopold, L.B. and Dunne, T. (1978). Water in the Soil. In: Leopold, L.B. and Dunne, T. *Water in Environmental Planning*, EEUU, Freeman.

Leopold, L.B. and Dunne, T. (1978). Water Loss from Lakes. In: Leopold, L.B. and Dunne, T. *Water in Environmental Planning*, EEUU, Freeman.

Leopold, L.B. and Dunne, T. (1978). Water Used by Vegetation. In: Leopold, L.B. and Dunne, T. *Water in Environmental Planning*, EEUU, Freeman.

Loucks, D.P. (1990) Water Resources Systems Models: Their role in planning. In: *Journal of Water resources Planning and Management*, Vol. 118, No.3, May/June 1992.

Macklin, M.G. and Lewin, J. (1997). Channel, Floodplain and Drainage Basin Response to Environmental Change. In: Thorne, C.R., Hey, R.D. and Newson, M.D. (eds.). 1997. *Applied Fluvial Geomorphology for River Engineering and Management*, John Wiley and Sons.

Macklin, M.G. and Lewin, J. (1997). Channel, Floodplain and Drainage Basin Response to Environmental Change. In: Thorne, C.R., Hey, R.D. and Newson, M.D. (eds.). 1997. *Applied Fluvial Geomorphology for River Engineering and Management*, John Wiley and Sons.

Maidment, D.R. (1993). GIS and Hydrologic Modelling. In: Goodchild, M., Parks, B.O. and Steyaert, L.T. (eds.) (1993). *Environmental Modelling with GIS*, Oxford, Oxford University Press.

Maiola, O.C., Gabellone, N.A. and Hernández, M.A. (2001) (ed) *Inundaciones en la Región Pampeana* (*Floods in the Pampas Region*). Universidad Nacional de la Plata, 2003.

Montgomery , D.R. and Dietrich, W.E. (1989). Source areas, drainage density and channel initiation. *Water Resources Research*. 25(8): 1907-1918.

Moore, I.D., Turner, K., Wilson, J. Jenson, S. And Band, L. (1993). GIS and Land-Surface-Subsurface Process Modelling. In: Goodchild, M., Parks, B.O. and Steyaert, L.T. (eds.) (1993). *Environmental Modelling with GIS*, Oxford, Oxford University Press.

Newson, M. (1994). Sustainable Integrated Development and The Basin Sediment System: Guidance from Fluvial Geomorphology. In: Kirby, C. (1994). *Integrated River Basin Development*.

O'Connel, P.E. and Todini, E. (1996). Modelling of rainfall, flow and mass transport in hydrological systems: an overview. *Journal of Hydrology* 175 (1996), 3-16.

Parks, B.O. (1993) The Need for Integration. In: Goodchild, M., Parks, B.O. and Steyaert, L.T. (eds.) (1993). *Environmental Modelling with GIS*, Oxford, Oxford University Press.

Pereira, L.S., Perrier, A., Allen, R.G. and Alves, I. (1999). Evapotranspiration: Concepts and Future Trends. *Journal of Irrigation and Drainage Engineering*, Vol. 125, No.2.

Querner, E.P. (1994). Aquatic Weed Control Options Evaluation with the Integrated Surface and Groundwater Flow Model MOGROW. In: Kirby, C. (1994). *Integrated River Basin Development*.

Ritzema, H.P. (ed) (1994). *Drainage Principles and Applications*. ILRI Publication 16, Second Edition. International Institute for Land Reclamation and Improvement, The Netherlands, 1994.

Sacks, L.A., Herman, J.S., Konikov, L.F. and Vela, A.L. (1991). Seasonal dynamics of groundwater-lake interactions at Doñona National Park, Spain. *Journal of Hydrology* 136 (1992), pp. 123-154, Elsevier, Amsterdam.

Shedlock, R.J., Wilcox, D.A., Thompson, T.A. and Cohen, D.A. (1993). Interactions between Grondwater and Wetlands, Southern Shore of Lake Michigan, USA. In: *Journal of Hydrology*, 141 (1993), pp. 127-155, Elsevier Science, Amsterdan.

Sivapalan, M. and Kalma, J.D. (1995). Scale problems in hydrology: Contributions of the Robertson Workshop. *Hydrological Processes – International Journal*, volume 9, issues 3-4 (237–482) and issues 5-6 (483-728). Wiley, 1995.

Steyaert , L.T. (1993) A perspective on the state of Environmental Simulation Modelling. In: Goodchild, M., Parks, B.O. and Steyaert, L.T. (eds.) (1993). *Environmental Modelling with GIS*, Oxford, Oxford University Press.

Tarboton, K.C., Neidrauer, C.J. and Santee, R.E. (2001). Application of the South Florida Water Management Model to Develop the Comprehensive Everglades Restoration Plan. In: Panigrahi, B.K. (2001). *Integrated Surface and Ground Water Management*, EWRI, ASCE.

Thorne, C.R. (1997). Channel Types and Morphological Classification. In: Thorne, C.R., Hey, R.D. and Newson, M.D. (eds.). 1997. *Applied Fluvial Geomorphology for River Engineering and Management*, John Wiley and Sons.

Tsakiris, G. And Todorovic, B. (1995). Computer aided Integrated Water Resources Management for Analysing Drought Conditions. In: Tsiourtis (ed.) 1995. *Water Resources Management under Drought or Water Shortage Conditions*. Balkema, Rotterdam.

Yen, B.C. and Riggins, R. (1991). Timescales for surface-subsurface modelling. In: Ritter, W.F. (ed). *Proceedings of the 1991 National Conference of the Irrigation and Drainage Division*, American Society of Civil Engineers, p.351-358.

Waltz, J.P. (1969). Groundwater. In: Chorley, R.J. (ed.). *Water, Earth and Man*. London, Methuen.

Wilsnack, N.M., Welter, D.E., McMunigal, C.L., Montoya, A.M. and Obeysekera, J. (2001). The Use of Modflow with New Surface Water Modules for Evaluating Proposed Water Management System Improvements in North Miami-Dade county, Florida. In: Panigrahi, B.K. (2001). *Integrated Surface and Ground Water Management*, EWRI, ASCE.

Wood, E.F., Sivapalan, M., Beven, K. and Band, L. (1988). Effects of spatial variability and scale with implications to hydrological modelling. *Journal of Hydrology*, 102 (1988) 29-47.

Wyness, A.J., Rippon, P.W. and Wardlaw, R.B. (1994). Application of an integrated model to chalk catchments. In: Reeve and Watts (eds) (1994), *Groundwater – Drought, Pollution & Management*. 1994, Balkema, Rotterdam.

- APPENDIX A -

THE RIO SALADO MASTER PLAN[1]

A.1 Master Plan Structure

The Master Plan being put forward is a wide ranging combination of measures which have been identified to address the constraints identified in the diagnosis study (see Chapter 3 of this thesis). They can be structured under the following headings:

- An institutional framework to enable effective planning and management,
- Non-structural measures to improve water management, agricultural production and environmental protection, to increase public awareness and to promote tourism,
- Supporting measures to promote economic development in the agricultural sector, and
- Structural measures to provide improved drainage and flood mitigation.

The proposed measures under each of the above headings are summarised in the following sections. The Master Plan is proposed as a flexible framework for development of the Rio Salado catchment. It does not prescribe to provide solutions to all of the problems which exist but it does provide the base and the tools to move forward. The need for monitoring and evaluation of the activities within the scope of the Plan, and the periodic review and revision of the proposals is strongly recommended.

[1] Text extracted and adapted from the Executive Summary of the Rio Salado Master Plan Studies (Halcrow, 1999).

A.2 Institutional Framework

An effective institutional framework for the planning and control of the development and the management of natural resources of the Rio Salado catchment is an essential foundation stone of the Master Plan, without which it is unlikely to meet the stated policy objectives. The proposed structure is based upon:

i. A de-centralised organisational structure, to allow planning, control and operation to be established and devolved to the most efficient management level;

ii. The necessary legislative and fiscal measures, to legitimise the organisations in the structure, to introduce cost recovery mechanisms, and to allow government to underwrite provision of credit and flood insurance services;

iii. The necessary capacity building measures to strengthen the capabilities of the organisations in the structure; and

iv. The preparation of effective management procedures and guidelines, to establish good practice in flood management, environmental management, and planning and development control.

Some of the programmes proposed to implement an effective institutional framework are listed below:

- Institutional restructuring programme
- Provincial and regional landcare organizations
- Landcare groups
- Development and management of operational boundaries

- Legitimisation of duties and powers of new institutional entities
- Programme for incentives to conservation practices
- Initiatives for cost recovery of operational and maintenance costs
- Capacity building for Provincial Team of the Master Plan
- Asset assessment programme
- Hydrometric network data management programme
- Flood control system management programme
- Environmental management programmes (fisheries, wetlands, sensitive channel design and maintenance manual, integrated natural resources management plan)
- Planning and evaluation guidelines for post project appraisal.

A.3 Non-structural and Supporting Measures

Within the Master Plan proposals there is a clear understanding that productivity increases will come about through both structural measures, that is those which improve physical infrastructure, and non-structural measures which are intended to address constraints that arise as a result of reducing the flood risk and/or improving drainage conditions. In summary, they are measures which are intended to act as catalysts to:

i. Promote agricultural change,
ii. Encourage the management and sustainable exploitation of environmental assets (including fisheries),
iii. Increase public awareness of the Master Plan,
iv. Develop the tourism sector in the area, and
v. Promote economic development in the agriculture sector.

The package of proposals is wide ranging but, collectively, they constitute an important component within the Master Plan. Some of the proposals are listed below:

- Soil conservation programmes for water, wind, compaction and loss of fertility, alkalinity, sodicity and erosion.
- Natural pasture improvement programme.
- Forestation in riparian areas
- Species and habitats management plans
- Public awareness and education programmes
- Development of tourism cooperatives
- Fisheries management plans
- Rural job creation programmes
- Training in farm business management programmes
- Livestock intensification programmes

A.4 Structural Measures

By far the major component of expenditure under the Master Plan will go towards structural measures and, for this reason, most attention has been focussed on the identification, analysis and evaluation of these projects. They can be grouped as follows:

- Flood control and drainage improvement projects,
- Farm level water management projects,
- Urban flood protection projects, and
- Rural road and road drainage improvement projects.

The structural projects proposed are summarised as follows:

(i) Flood control and drainage improvement projects are grouped geographically as described as follows:

- Rio Salado /Ao. Vallimanca/Ao. Las Flores – small scale channel and embanking works, plus major diversions and alleviation channels;

- Northwest – primary and secondary drainage works plus storage and regulation where possible; and

- Zona Deprimida – rehabilitation and improvement of existing drainage canals, plus small scale embankments to the arroyos of the Sierra de Tandil.

The scope of works also includes: water level control structures, bridges and rehabilitation/improvement of rural roads. A quantified summary of the major components proposed is given in Table A.1.

(ii) Urban flood protection projects for sixteen towns, including new works and rehabilitation of existing defences, and comprising: embankments, storage reservoirs, control structures, watercourse improvement and urban drainage pumping, together with associated planning, environmental and institutional measures.

(iii) Rural road and road drainage improvements, with the emphasis being on raising of rural roads where necessary and increased cross drainage capacity, plus cross drainage improvements on selected main roads.

Figure A.1 shows the main components of the proposed structural measures.

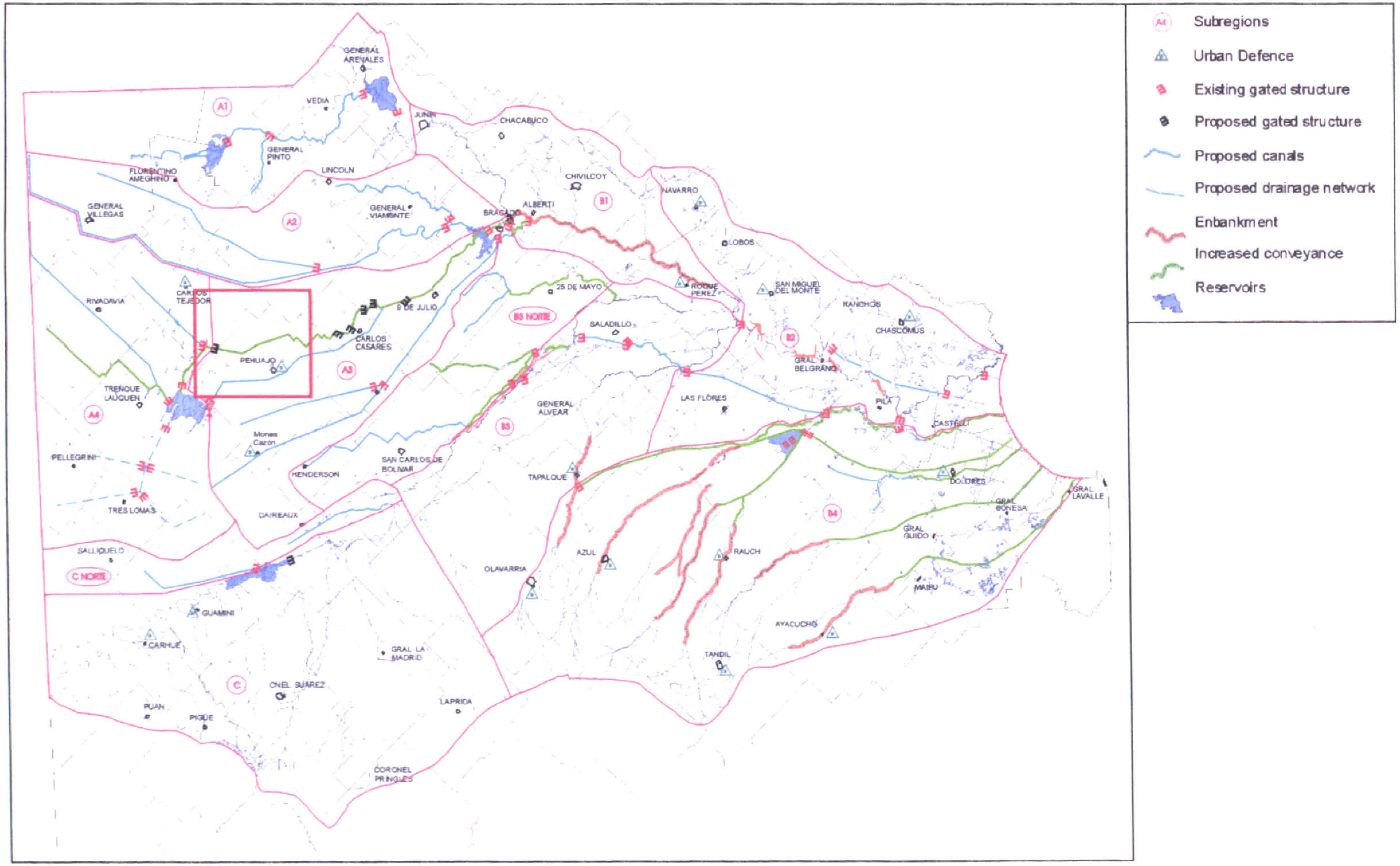


Figure A.1: Río Salado Master Plan. Proposed Structural Measures.

Drainage and mitigation works in the Northwest

Item	A1	A2	A3	A4	B3N (Norte)	CN (Norte)	Total
Primary drainage channels (km)	196	446	535	576	320	134	2207
Secondary drainage channels (km)	1281	1710	2495	3000	1606	533	10625
Bridges (No)	16	33	52	50	26	11	188
Control works (No)	9	21	24	25	9	6	94
Reservoirs (No / Hm^3)	2/380	-	1/130	1/610	-	1/278	4/1098
Improvements in rural roads	215	195	229	155	267	116	1177

Mitigation and improvement works in Río Salado/Ao Vallimanca / Ao Las Flores

Item	Upper Salado	Lower Salado	Ao Vallimanca/ Saladillo/Las Flores	Total
Embankments (km)	200	130	30	360
Increase capacity (km)	200		30	230
Removal of constrictions (No)		7		7
Improvements in bridges (No)	1	8	4	13
Flood alleviation channels (No)		67	150	217
Bridges (No)		7	20	27
Flood alleviation structures (No)		13	8	15

Mitigation and improvement works in Zona Deprimida

Item	
Rehabilitation of high level carriers and associated structures (km)	600
Improvements in minor channels (No)	varios
Reservoirs (No / Hm^3)	1/1000
Improvements in water courses (km)	170
Bridges (No)	15
Control works (No)	14
Embankments in hillslope courses (km)	400

Urban flood defense works

Item	No of urban locations
Cities without defense works	10
Cities with existing defense systems that need rehabilitation and/or enlargement	6

Table A.1: Summary of drainage and flooding mitigation works.

A.5 Implementation of the Master Plan

There are many factors which can influence the formulation and programming of the measures proposed in a master plan. The general guidelines which have been adopted in this case are summarised as follows:

i. To ensure institutional development before infrastructure development,

ii. To ensure flexibility through progressive, staged development,

iii. To phase development of infrastructure to maintain a situation of no detriment and/or equity of benefit,

iv. To link the rate of implementation to accord with social acceptability,

v. To link the rate of implementation to accord with availability of finances,

vi. To maximise net economic benefits, and

vii. To adjust to political pressure.

A 15-year implementation period was suggested as being a realistic minimum for the full implementation of the Master Plan. In the short term, a first phase development could be a commitment to proceed with:

(i) The first steps for institutional change requiring: establishment of a multi functional Provincial Master Plan Team, establishment of a transitional Provincial Catchment Commission, establishment in a pilot area of a Regional Catchment Council, initiation of the formation of Catchment Coordination Committees, appointment of a Regional and, in a pilot area, a Sub-regional Landcare coordinator, and legitimisation of new entities and of boundary revisions within the framework of the Codigo de Aguas (Water Act).

(ii) The priority non-structural and supporting measures including some of those: to conserve land fertility, to increase agricultural productivity, particularly in the livestock sector, and to enhance environmental assets, the emphasis being towards habitat and fisheries management plans.

(iii) The urban flood protection works for six cities, including: Olavarria, Azul and Tandil, and rural road improvement works in six partidos in the Northwest and Rio Salado Superior areas.

(iv) A limited programme of flood control and drainage works, including improvements in some of the Northwest, probably Sub-regions A1 and A3, mitigation and local improvements along the lower and upper Rio Salado, and rehabilitation of existing infrastructure in the Zona Deprimida and along the lower Ao Vallimanca.

The programme proposed is logical, but it is also flexible and it will, no doubt, change as the government and public discussion of the Master Plan continues, and as the more detailed studies proceed.

A.6 Risks and Uncertainties

The risks and uncertainties which could affect the Master Plan are numerous. They include:

- Although the database is a compilation of what exists there are, nevertheless, limitations within it which may prejudice analytical conclusions, and this points to the need for continued and improved data collection

- There is also a need to monitor performance in relation to design criteria and, thereafter, to review and revise the works accordingly, otherwise there is a risk that problems may not be solved, or solved inefficiently.

- There is a risk that the changes needed to solve the problem of inadequate operation and maintenance will not be forthcoming, and the works will not be able to function as designed.

- The predicted benefits in the agriculture sector, and hence the success of the Master Plan, depend on the response of the producers and there is a risk that they will not respond as assumed if they are not informed, consulted and allowed to play their full part in the development process.

- There remains a risk that the proposals for institutional change may be too radical for some views and that they will not get political support.

- The integrated approach is fundamental to the success of future stages of the Master Plan but there is a risk that structural projects will be given priority, at the expense of the equally important non-structural and supporting measures.

External factors, such as movement of international prices, climate change and sea level rise, are out the control of the Master Plan but they present a risk that performance will not match that predicted.

A.7 The Impact

A.7.1 Cost Estimates

The cost estimates for the structural measures have been calculated based on prefeasibility level designs for the works and using unit rates used by DPH for similar works. They include: primary and secondary works, control works, bridges, rural roads, land acquisition, study, design and supervision, environmental mitigation measures, and physical contingencies. These last three items are taken as percentages of the base costs and included at the rates of 5%, 5% and 25% respectively.

Table A.2 summarises the costs for the structural components. They total AR$1830 millions made up as follows:

Measure	Cost
Improvement/mitigation along the Rio Salado/Ao Vallimanca/Ao Las Flores corridors.	$406 millions
Drainage and flood mitigation in the Northwest.	$863 millions
Rehabilitation/improvement in the Zona Deprimida.	$561 millions
Total	**$1830**

Table A.2: Summary of costs of structural measures (values in AR$ when 1AR$=1US$)

A design standard of 1:10 years has been adopted for the works in the Northwest and along the Rio Salado/Ao Vallimanca/Ao Las Flores corridors, this standard having been chosen on the basis of consistently higher economic returns in all sub-regions of the Northwest compared to the 1:5 years standard. For the Zona Deprimida, where economic returns are much lower, a standard of 1:2 years has been used.

In addition, AR$55 millions is included for urban flood defence works. The design standard for these works is to protect the cities against a flood with a recurrence interval of once in 100 years.

The cost estimates for the institutional reform, non-structural and supporting programmes are summarised in Table A.3. They total AR$34 millions for the programme of institutional change and reform, and AR$25 millions for the non-structural and supporting measures. It should be noted that, in some cases, the costs given are those for the additional studies and preparatory work which will be necessary to better define the programmes, and not the expected full cost of the programmes.

Measure	Cost (million AR$)
Organisational structure	8.5
Legislative and fiscal measures	1.4
Capacity building	3.4
Management procedures and guidelines	21.1
Agricultural measures	13.7
Environmental measures	2.3
Consultation and public awareness	0.6
Tourism measures	0.3
Fisheries measures	0.9
Agricultural support measures	7.1
Total	**59.3**

Table A.3: Summary of costs of institutional and non structural measures.

A.7.2 Economic Evaluation

The economic evaluation has been applied only to the drainage and flood mitigation works, and not to the urban flood defences, rural road improvements and non-structural measures. For the evaluation, project costs and benefits have been converted from financial to economic prices by applying conversion factors.

Neither costs nor benefits for the institutional, non-structural and supporting programmes have been included in the economic analysis, this being the generally accepted convention for evaluation of development programmes.

Construction costs for all structural works, excluding expropriation, design and supervision, and physical contingencies, have been converted from financial to economic prices by applying a standard conversion factor of 0.72. Economic values for agriculture and livestock inputs and outputs have been calculated at import or export parity prices. World market prices are the export prices of the major agricultural commodities, and taxes and duties have been deducted from input prices.

Productive land which will be required for construction of canals and reservoirs has been valued at present value of the net farm income which will be foregone as a result of implementing the project.

Annual operation and maintenance costs have been estimated at 2% of total investment costs in economic prices.

Benefits to crops and livestock have been measured as net incremental benefits, that is the difference between the net value of farm production in the "without project" and the "with project" cases. They include: reduced losses of crops and livestock production and on-farm infrastructure caused by flooding/waterlogging, and changes in land use as a response to reduced risk of flooding/waterlogging.

The benefits attributable to public infrastructure in rural areas have been estimated as the total value of avoided flood damage to the infrastructure, that is the reduced cost of repair of damage.

All project benefits have been weighted by flood event probabilities. A "damage-frequency" curve has been derived based on expected levels of loss for different flood events, from which the "average annual expectation of loss" has been calculated.

Benefits have been phased in accordance with the rate of completion of secondary canals in a particular sub-region. For benefits from avoided flood losses the assumption is a lag of one year, whilst for changes in land use it is assumed that full benefits will not be achieved until the fifth year after completion of the canals.

For the economic evaluation the project life has been assumed to be 30 years, that is the useful life of the main categories of structure required, assuming adequate operation and maintenance. The following criteria have been used: net present value, cost/benefit ratio, and economic internal rate of return.

The Extensive Option, which includes all of the structural components yields the best returns, with an economic internal rate of return of 13.4%, which increases to 16% if works in the Zona Deprimida/Sierra de Tandil are excluded. These values increase by 1% if the implementation period is extended from 15 to 20 years. The sensitivity analysis indicates that results would remain acceptable even with relatively large changes in costs or benefits.

Although the development of the Zona Deprimida is not economically attractive there are arguments for its inclusion on the basis of social equity and the fact that the Master Plan professes to be a programme for development of the whole catchment. Also the fact that about 24% of the total production of meat in the catchment comes from this area should not be ignored. It is recommended that development proceeds over the whole catchment, albeit with works in the Zona Deprimida being to a lower design standard than other areas.

With implementation of the measures proposed in the Master Plan it is expected that widespread and significant increases in production in the agriculture sector will result. The projected annual increases in production, in terms of crops, livestock and dairy, and divided by sub-region are given in Table A.4. Values are given both as tonnes and as the percentage increase on present production at full project development. Overall it equates to an increase of about 10% on present annual production, that is over 1 million tonnes of crops and 150,000 tonnes in the livestock sector.

A.7.3 Social Impact

The success of the Master Plan and its sustainability will depend on its social impact, that is the number of people who will benefit and those who will suffer, and their distribution both within a sub-region and within the catchment as a whole. Unless there is reasonable distribution throughout, there will not be equity of benefit, the Plan will not gain widespread support and it will not encourage majority stakeholder participation.

With implementation of the measures proposed the expected number of beneficiaries in the Northwest, which has been taken as the farm families of owners, managers and labourers, totals about 179,000. A comparable figure for the whole catchment, that is farm family members, is about 400,000, so about 45% of these are expected to benefit in the principal benefit area. Along the river corridors and in the Zona Deprimida the rescued areas are smaller and the population density lower. In these areas an estimate of farm family members who are likely to benefit from the proposals is of the order of 70,000 and so, for the whole catchment, over 60% of those directly dependent on the land should benefit from the works.

Small producers are one of the poorest social groups in the area. Statistics suggest that about 50% of this group operate in the Northwest and, of these, about 30,000 will directly benefit. For the other parts of the catchment a conservative estimate is that a further 15,000 will benefit.

Apart from those benefitting from drainage and flood mitigation measures, a wider section of the community will benefit from the improvement to rural roads and flood protection of urban centres, and from access to some of the programmes of non-structural and supporting measures.

A.7.4 Environmental Impact

A strategic Master Plan of this scale has the potential for significant environmental effects. The role of the environmental impact assessment in the development of such a plan is to minimise adverse environmental effects, maximise benefits and ensure the selection of an environmentally sustainable strategy.

The most important potential impacts are:

- The anticipated benefits to agricultural and livestock production, which provide significant regional and national economic benefit, within a general framework of sustainable agricultural development; and

- The potential for significant loss and modification of wetland and floodplain areas.

These two aspects are generally antagonistic in nature. It is not possible to create agricultural/livestock benefits, of the nature required by the objectives of the Master Plan, without some drainage of semi-natural areas and changes in land use. However the proposals attempt to strike a balance between land use change and conservation of critical /valuable natural habitats. Mitigation of impacts has largely been through the iterative development process and it is anticpated that the ecologically sensitive design proposals for new channels and flood attenuation areas will bring considerable ecological and recreational benefit.

Notwithstanding the above, and given the lack of understanding of the interactions between land use, flooding and natural habitats, it is considered that there is significant environmental risk involved with implementation of the structural proposals. This risk will be managed through implementation of the extensive range of non-structural measures, and the proposals for institutional and environmental capacity strengthening. In addition, the integrated natural resources management plan offers the opportunity to provide appropriate environmental management and sustainable development within the region in the future, against a natural trend (do-nothing scenario) of continued adverse impacts from ad-hoc and non-strategic drainage works and other development.

		A1	A2	A3	A4	B1	B2	B3	B4	C	Total
Productive land	km^2	1,135	1,459	1,061	1,476	204	632	1,894	3,922	388	12,125
Productive land relieved from waterlogging	km^2	278	688	1,870	1,890	25	56	1,541	70	438	6,854
Increased in agricultural productivity	t/year	46,699	78,573	231,503	291,433	6,912	25,361	169,940	52,271	119,788	1,022,480
Increased in livestock productivity	t/year	19,603	23,537	21,359	34,726	994	3,992	16,645	17,239	7,184	145,279
Increased in dairy productivity	t/year	3,601	1,990	1,622	2,433	118	105	1,896	290	68	12,124
Economic TIR	%	21.7	16.	17.0	22.6	negative	negative	36.5	negative	32.7	14.3
Net Present Value @ 10%	$ millon	68.76	57.70	83.04	181.44			116.53		74.05	192.74
Increase on the existing agricultural productivity	%	4	7	21	22	0	4	11	6	8	10
Increase on the existing livestock productivity	%	14	18	13	14	2	4	6	5	2	8
Increase on the existing dairy productivity	%	31	18	12	14	1	1	13	2	4	11

Table A.4: Benefits

Notes

Estimated production from a full implementation of the project.
Include benefits per losses avoided by floods, expressed in annual probability of losses.
Include changes in land use as result of the higher investments due to the reduced risk of flooding

- APPENDIX B -

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iSISMOD

B.1 Introduction

This Appendix complements Chapter 6 of the thesis presenting more detailed information on the two programs that form iSISMOD: MODFLOW and iSIS Flow, covering their governing equations and overall structure.

Also, the runtime parameters and different data files associated to iSISMOD are included in section B.2, finalising in Section B.3 with the presentation of the results of the test cases used to verify the software development. The corresponding run logs of the test case simulations are presented in Appendix C.

B.2 Information on iSIS and MODFLOW

B.2.1 MODFLOW

B.2.1.1 Overall Structure

The program consists of a main program (*"modflow.f"*) and a series of independent subroutines called "modules" that perform the hydraulic computation for each element into which the aquifer system was discretized, such as: abstraction wells, recharge, evapotranspiration, leakage from water bodies, drains, etc. Figure B.1 presents the overall structure of MODFLOW.

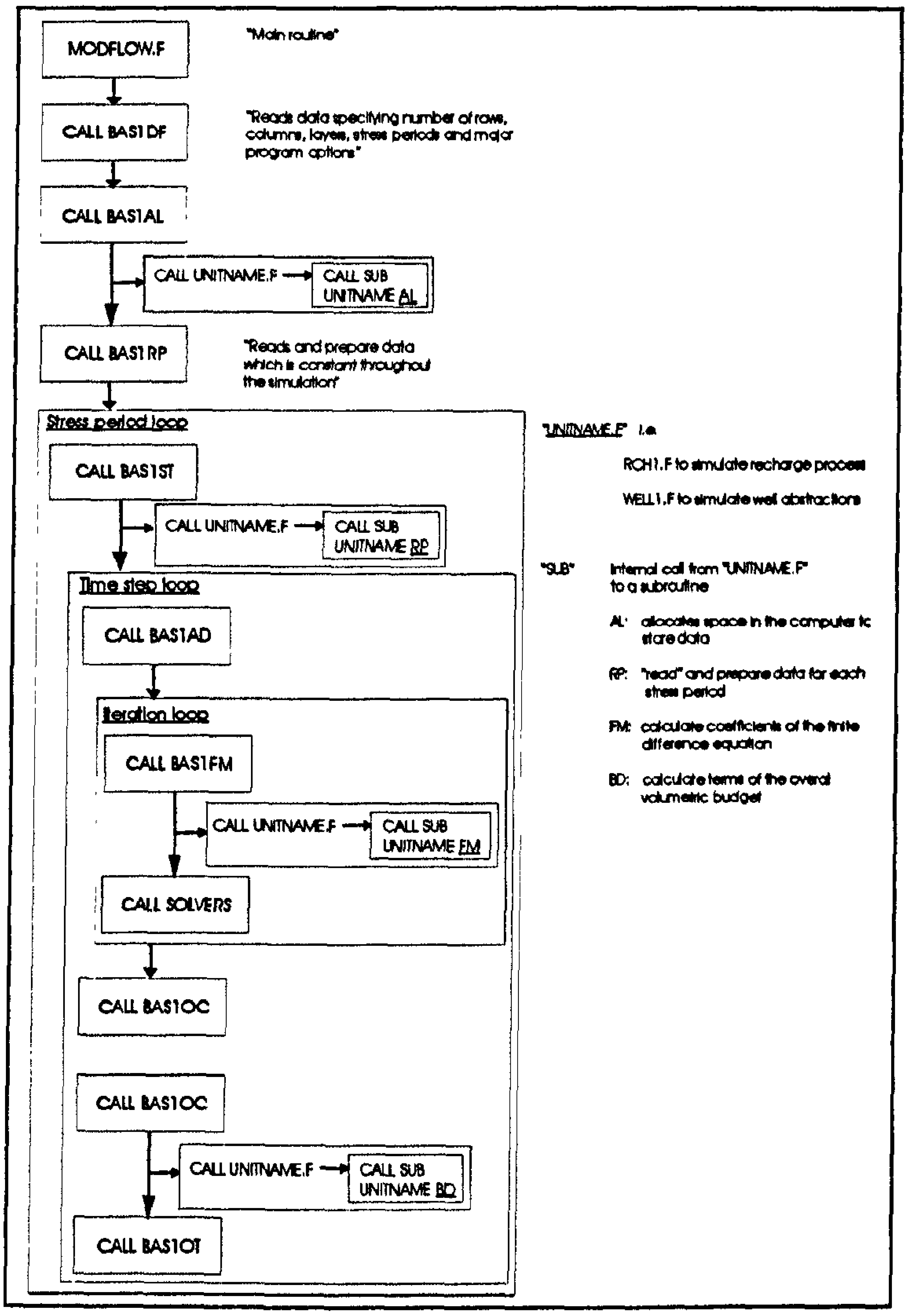


Figure B.1: Overall Structure of MODFLOW.

B.2.1.2 Governing equations

The governing equation used in MODFLOW to solve the three-dimensional movement of water in a saturated porous media is the Darcy equation embedded into the continuity equation, as follows:

$$\frac{\partial}{\partial x}\left(K_{xx}\times\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\times\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\times\frac{\partial h}{\partial z}\right)-W=S_s\times\frac{\partial h}{\partial t}$$

where,

Kxx, Kyy and Kzz are values of hydraulic conductivity along the x,y and z coordinate axes, which are assumed to be parallel to the major axes of hydraulic conductivity (LT^{-1})

h = groundwater head (L) W = volumetric flux per unit volume and represents sources and/or sinks of water (T^{-1})

Ss = specific storage of the porous media (L^{-1})

t = time (T)

The above equation, together with an appropriate set of boundary and initial conditions, constitutes a mathematical representation of a groundwater flow system. It yields a time varying head distribution that, in turn, measures the energy of flow, the volume of water in storage, and also allows calculation of directions and rates of water movement.

B.2.1.3 Discretization, Conductance and Storage formulation

A typical aquifer is spatially discretized in a mesh of block cells, which are described in terms of rows, columns and layers, using a typical i (row direction), j (column direction), k (layer direction) indexing system. Within each cell, there is a point called a node for which the head is calculated. Nodes are located at the centre of each block cell, which is termed a "block centered" formulation.

Solution of the continuity equation is carried out using a finite difference approach: the sum of all flows entering and leaving a cell should be equal to the rate of change in storage within the cell. Following the convention that a flow is positive if it enters a cell, flow into a typical cell i,j,k in the row direction from cell $i,j-1,k$ is given by Darcy's law as:

$$q_{i,j-1/2,k} = KR_{i,j-1/2,k} \times \Delta c_i \times \Delta v_k \times \left(\frac{h_{i,j-1,k} - h_{i,j,k}}{\Delta r_{j-1/2}} \right)$$

where,

$h_{i,j,k}$ = head at node *i,j,k* and $h_{i,j-1,k}$ at node *i,j-1,k.*

$q_{i,j-1/2,k}$ = discharge through the face between cells *i,j,k* and *i,j-1,k*

$KR_{i,j-1/2,k}$ = hydraulic conductivity along the row between nodes *i,j,k* and *i,j-1,k* (LT_{-1})

$\Delta c_i x \Delta v_k$ = area of the cell faces normal to the row direction, and

$\Delta r_{j-1/2}$ = distance between nodes *i,j,k* and *i,j-1,k.*

It is important to interpret the conductance formulation correctly in that the term $KR_{i,j-1/2,k}$ is the effective hydraulic conductivity for the entire region between the adjacent nodes, as *i,j-1/2,k* does not represent a specific physical point in the system.

The above equation can be also re-written, including the conductance term as the product of hydraulic conductivity, by the cross sectional area of flow divided by the length of the flow path (i.e. the distance between the nodes). Depending on the type of aquifer (for each of the layers involved in the model), conductance can be constant throughout the simulation if the layer is confined and the saturated thickness does not vary with time. If the layer is unconfined, then the saturation thickness varies with time and the conductance is updated every time step or stress period accordingly.

The same principle applies to each of the six faces of a cell, to take into account of flows from each of the six adjacent cells.

The mass balance needs to be completed taking into account of flows from features external to the aquifer. These flows may be dependent on the head in the receiving cell but independent of all other heads of the aquifer, or they may be entirely independent of head in the receiving cell. Therefore, flow from outside the system is represented by:

$$a_{i,j,k,n} = p_{i,j,k,n} \times h_{i,j,k} + q_{i,j,k,n}$$

where,

$a_{i,j,k,n}$ represents flow from the nth external source into cell i,j,k (L^3T^{-1}), and $p_{i,j,k,n}$ and $q_{i,j,k,n}$ are constants (L^2t^{-1} and L^3T^{-1}, respectively).

Vertical conductance terms are calculated within the model using data from an input array, which incorporates both thickness and vertical conductivity in a single term, using cell areas (horizontal) calculated internally from cell dimensions. Therefore, the vertical conductance can be expressed, for a vertical hydrogeological layer g, as follows:

$$C_g = \frac{K_g \times DELR_j \times DELC_i}{\Delta z_g}$$

where,

Kg = vertical hydraulic conductivity,
$DELR_j$ *and* $DELC_i$ = row and column dimensions respectively, and
Zg = vertical distance between two adjacent nodes in the vertical direction (*i,j,k and i,j,k+1*)

In MODFLOW, a term called "vertical leakance" (*Vcont*) is read, which is defined as the conductance of the vertical element divided by the cell area, incorporating the hydraulic conductivity and the thickness. The program calculates vertical conductance internally by multiplying Vcont by cell area.

$$Vcont_{,j,k+1/2} = \frac{Kz_{i,j}}{\Delta z_{k+1/2}}$$

Boundary cells in MODFLOW can be grouped in two categories: "constant head cells" and "no flow cells". The first set of cells are those for which the head is specified in advance, either constant for the entire simulation or as pre-defined function of time. 'No flow' cells are those for which no flow into or out of the cell is permitted. The remaining cells of the model are termed "variable head cells", which means that their heads are free to vary with time.

MODFLOW allows for a change in the storage term, depending on whether a cell is under a confined situation during the entire simulation of whether it changes to a water table situation (unconfined) when the water table falls below the top of a cell.

If the storage coefficient remains constant during the simulation, the storage formulation is based on the following expression, that for a cell *i,j,k* is:

$$\frac{\Delta V}{\Delta t} = SS_{i,j,k} \times (\Delta r_j \Delta c_i \Delta v_k) \times \frac{h^m_{i,j,k} - h^{m-1}_{i,j,k}}{t_m - t_{m-1}}$$

where, SS = specific storage of the material, which represents the change of volume of a unit of porous media due to a unit change in gradient. MODFLOW uses the concept of "primary storage coefficient" as

$$SC1_{i,j,k} = SS_{i,j,k} \times (\Delta r_j \Delta c_i \Delta v_k)$$

The input to the program for a confined layer is the product of $SS_{i,j,k} \times \Delta v_k$

For an unconfined layer, the value entered in the program directly is the specific yield, termed as the "secondary storage coefficient". In both cases, MODFLOW reads the primary and secondary coefficients and multiplies them by cell area to calculate the storage term.

B.2.1.4 Water Balance Formulation

MODFLOW calculates a water budget for the overall model as an independent check on the acceptability of the solution, as it is calculated independently of the equation solution process. Each flow component package (recharge, evapotranspiration, stream, etc) calculates its own contribution to the budget. The total budget as printed in the output file (*"filename.out"*) does not include internal flows between cells, but only flows in and out of the entire model.

Inflows are printed separately from the outflows, adopting the following convention: water entering storage is treated as an outflow from the "flow system", while water released from storage is treated as an inflow to the "flow system". The difference between total inflow and total outflow is printed as percentage difference, which should be kept small for every stress period and for the entire simulation.

B.2.1.5 Runtime Parameters and Options

MODFLOW requires a superfile (*"filename.mfs"*) that stores the names of all the files needed to perform a simulation. Typical files usually contained in a superfile are:

(i) basic package file (*"filename.bas"*) that stores the data that define the model: number of rows and columns, number of stress periods and initial and boundary conditions,

(ii) aquifer definition file (*"filename.bcf"*) that stores the data required to define the hydrogeological and geometrical properties of the aquifer, such as conductivities, storativities, bottom and elevation for each vertical layer, type of aquifer, etc.

(iii) stress files that store the data that define each of the element that form part of the aquifer system, such as recharge (*"filename.rch"*), evapotranspiration (*"filename.evt"*), abstraction from pumping wells (*"filename.wel"*), etc.

(iv) output file where some of the results and the balance calculation will be stored (*"filename.out"*),

(v) mathematical solver file, which is the file that defines the data required for each of the algorithms available to solve the matrix from the finite difference scheme (*"filename.pcg"*).

Each of the files is stored in ASCII format and can be constructed and edited either manually or through any of the available commercial interfaces, such as GMS or Visual Modflow.

B.2.2 iSIS Flow

B.2.2.1 Overall Structure

Figure B2.2 presents the overall structure of iSIS. The program is basically formed by a core routine that manages execution of a simulation, a set of routines to perform the hydraulic computation for each type of element (by calculating the coefficients that result from the discretisation of the Saint Venant equations), a routine to solve the resulting matrix, and a set of routines to manage the presentation of results.

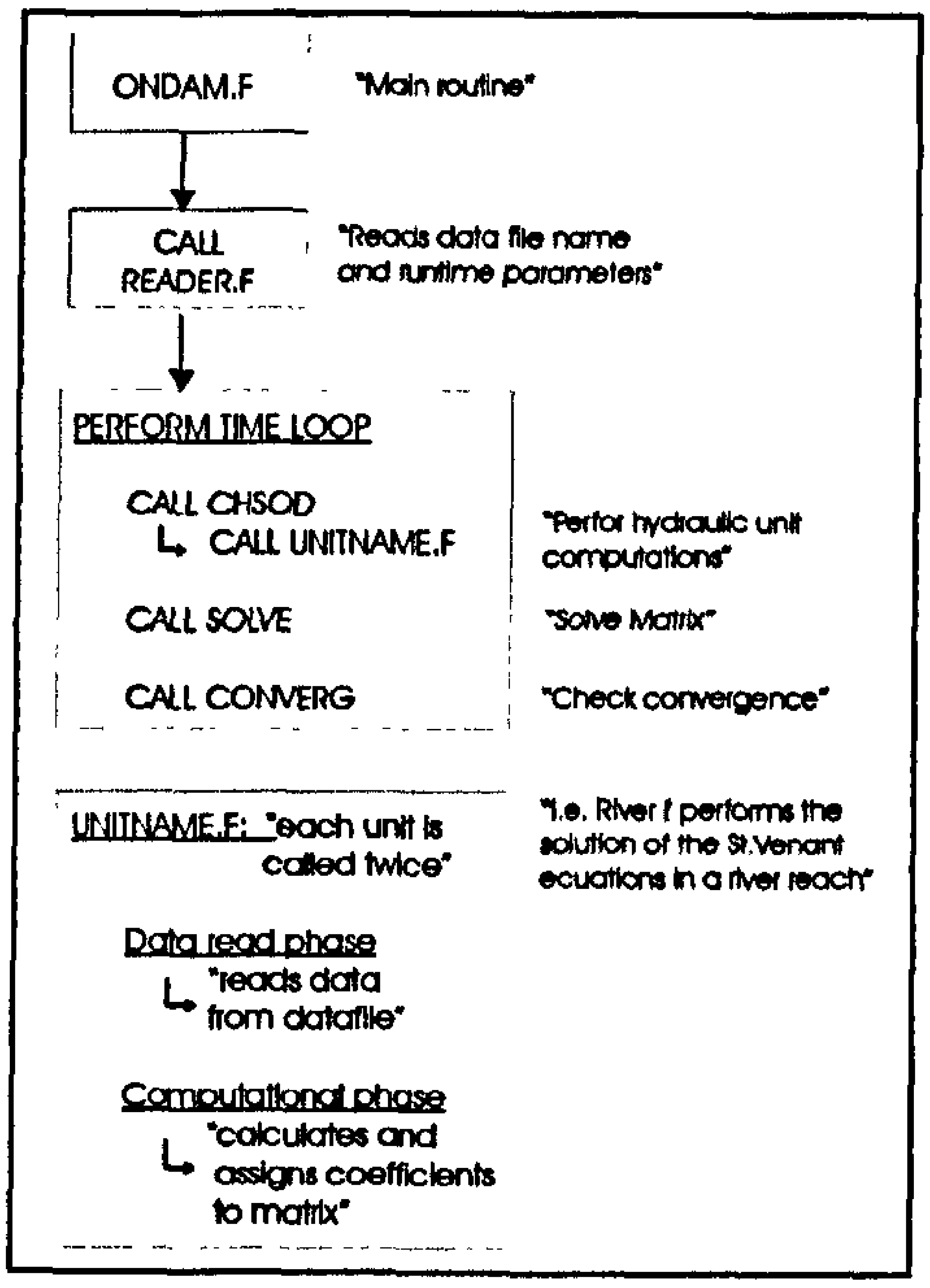


Figure B.2: Outline Structure of iSIS Flow

B.2.2.2 Governing equations

River modelling involves interaction of the channel and external and internal controls, taking into account the conservation of mass and momentum of the water body along the channel network.

The movement of water flowing in an open channel is described by the Saint Venant equations for conservation of mass and momentum. The first principle is represented by the continuity equation, which establishes a balance between the rate of rise of water level and the net flow entering a channel reach. The conservation of momentum leads to the dynamic equation, which establishes a balance between inertia, diffusion, gravity and friction forces.

Therefore, the governing equations are the continuity equation:

$$\frac{\delta Q}{\delta x}+\frac{\delta h}{\delta t}+q=0$$

Where q represents a distributed (i.e. lateral) inflow ($m^3/s/m$).

and the momentum equation:

$$\frac{\partial Q}{\partial t}+\frac{\partial}{\partial x}\left(\frac{\beta\times Q^2}{A}\right)+g\times A\times\frac{\partial H}{\partial x}-g\times A\times S_f=0$$

Where, S_f = friction slope, expressed as:

$$S_f=\frac{Q\times Q}{K^2}$$

Where K is the channel conveyance parameter, calculated according to Manning's equation as:

$$K^2=\frac{A^2\times R^{\frac{4}{3}}}{n^2}$$

and

$$R=\frac{A}{P}$$

R = hydraulic radius, P = wetted perimeter and n = roughness coefficient.

For fully sub-critical flow, the program requires an independent boundary condition specified at both the upstream and downstream ends of the model. For a fully supercritical regime, two independent boundary conditions (usually flow and stage) are required at the upstream boundary of the model. Boundary conditions must be correctly specified since the uniqueness of the solution depends upon them: a discharge hydrograph upstream and a stage hydrograph downstream, or a discharge hydrograph upstream and a rating curve downstream, usually lead to a well posed set of equations.

In the representation of a river network, channel reaches are separated by internal boundaries which may be control structures, losses, reservoirs or junctions (confluences or bifurcations). These boundary conditions impose a relationship between stages and discharges at the nodes involved.

B.2.2.3 Runtime Parameters and Options

All the data required to define the hydraulic properties of a channel network and its associated hydraulic structures are specified in an ASCII data file ("filename.dat"), that can be created either manually or using the iSIS Windows interface. The data file also contains the boundary and the initial conditions required to solve the governing equations of the problem.

Basically, two types of simulations can be performed with iSIS: steady state (flows and depths constant through time) and unsteady state (flows and depths varying with time). When a simulation is performed, the iSIS simulation control panel prompts for the run time parameters required to perform a run; the most important are:

- (i) name of the data file,
- (ii) type of simulation (steady or unsteady),
- (iii) type of solution method (if the choice is steady),
- (iv) start and end time of the simulation,
- (v) time step required for the simulation.

Two types of methods are available to solve a steady state problem: the *"direct method"* and the *"pseudo time stepping method"*. The first is based on the solution of Saint Venant equations (written as ordinary differential equations for the steady state case) using the Runge-Kutta method and Kirchoff's law to deal, iteratively, with flow splits at bifurcations and confluences. The strength of this method is based on the small amount of information required to perform the simulation, as initial conditions are not needed, except for the downstream end of the network, from where the calculation starts. This method also checks whether a solution is grid dependent and, if needed, automatically adds internal interpolated cross sections, alerting the user on the need of more data to define a channel reach.

The pseudo-time stepping method is based on the solution of the differential equations using the same finite difference scheme used for the solution of an unsteady run (the Preissmann 4-point scheme). Initial conditions (flows and depths) are required for each node of the system and the steady state run is achieved by maintaining a constant flow throughout the simulation.

After a run is performed, a series of output files are created. The key files are:

(i) a diagnosis file in ASCII form (*"filename.zzd"*)

(ii) a file containing the steady state results in ASCII form (*"filename.zzs"*)

(iii) a file with the unsteady results in binary form (*"filename.zzn"*) which can only be accessed through the iSIS Workbench.

B.3 iSISMOD – Runtime Parameters

Table B.1 presents the various prompts that appear when iSISMOD is executed:

Prompt	Description	Example
file identifier >	iSIS data file	test5.dat
total number of monitors required >	specifies iSIS monitors to check secondary information produced in a simulation	0
steady (s), unsteady (u) or boundary (b) mode >	choose between steady, unsteady state simulation or boundary mode (hydrological)	u
time (hrs) at which run is to start >	of the iSIS simulation	0
time in (hrs) at which run is to finish >	of the iSIS simulation	24
time step (sec) >	of the iSIS simulation	360
enter time interval to save data .... >	of the iSIS simulation	1
initial conditions from steady (s) or data file (d) >	Steady means that initial conditions are read from a previously executed iSIS steady state run.	s
Network check (y/n) >	Check connectivities in iSIS	y
Write OTTA file (y/n) >	not applicable.	n
Write iSIS Water Quality file (y/n) >	not applicable.	n

Is coupling with Modflow required (y/n) >	-	y
Enter the name of the MODFLOW superfile >	File that stores all the file names required to perform a MODFLOW simulation. (see below for template)	test5a.mfs
Enter iSIS-MODFLOW control file >	File that store the connectivity between iSIS nodes and MODFLOW cells. (see below for template)	test5.mfl
Enter iSIS-MODFLOW plot file >	File that stores information to produce time series of water levels for longitudinal profiles, cross sections and individual cells. (see below for template)	test5.plt

Table B.1: Prompts in an iSISMOD Simulation.

A set of templates of the files required to perform an iSISMOD run is presented below:

Modflow Superfile ("filename.mfs")

`LIST 26 test5.out`
`BAS1 1 test5.bas`
`BCF3 11 test5.bcf`
`OUT1 10 test5.oc`
`HEAD -30 test5.hed`
`CCF -40 test540.ccf`
`PCG2 12 test5.pcg`
`MT3D -29 test5.hff`
`ISIS 31 test5.str`
`END`
	A superfile lists all the files needed by the MODFLOW program to perform a simulation. The number indicates what file unit is used to read and write data.

iSIS Datafile ("filename.dat")

```
TEST MODEL combined river + reservoir
         5     0.750     0.900     0.010     0.001         8
    20.000     0.010     0.010     0.700     0.100     0.700     0.000
QTBDY inflow to river
qtrivl
         2     0.000     0.000     hours     EXTEND    LINEAR
      1.00         0
      1.00    1000.0
RESERVOIR
qtrivl    rivlus
5
95.0          500.0
98.0       250000.0
99.0      2250000.0
100.0     6250000.0
SPILL
rivlus  nodel
     1.000     0.700
         4
     0.000    199.00
     1.000    199.00
    10.000    199.00
    11.000    199.00
RIVER
SECTION
nodel
   400.000
         5
  -12.5000    20.500    0.03000    1.000
  -12.5000    10.500    0.03000    1.000
    0.0000    10.500    0.03000    1.000
   12.5000    10.500    0.03000    1.000
   12.5000    20.500    0.03000    1.000
RIVER
SECTION
node2
     0.000
         5
  -12.5000    20.000    0.03000    1.000
  -12.5000    10.000    0.03000    1.000
    0.0000    10.000    0.03000    1.000
   12.5000    10.000    0.03000    1.000
   12.5000    20.000    0.03000    1.000
QHBDY
node2
        50
     0.000    79.000
     0.437    79.133
     1.380    79.267
     2.696    79.400
INITIAL CONDITIONS
 label   ?      flow     stage froude no velocity    umode    ustate        z
qtrainl y     10.000    66.996    0.364    2.790   213.225    0.000   61.000
qtrivl  y     10.000    66.996    0.364    2.790   213.225    0.000   61.000
rivlus  y     10.000    66.996    0.364    2.790   213.225    0.000   61.000
rivlds  y     10.000    66.996    0.364    2.790   213.225    0.000   61.000
nodel   y     10.000    66.996    0.364    2.790   213.225    0.000   61.000
node2   y     10.000    66.386    0.364    2.790   213.225    0.000   60.390
```

This sample iSIS data file shows a network comprised of a 2-node river channel reach and a reservoir connected to it by means of an irregular weir (spill).

Tables B.2 and B.3 describe the structure and content of an iSISMOD control file; the format of the data is indicated in brackets. Figures 6.10 and 6.11 show two sample control files: one where the interaction is performed with a river channel and another one where the interaction is with a reservoir unit. In both cases multiple aquifer cells are defined for an individual iSIS node.

Line	Column							
	1	2	3	4	5	6	7	8
1	Header							
2	Header							
3	Keyword (describes the type of iSIS unit to interact to; i.e. River) *(a10)*							
3	Interpolation index *(i4)*		Interpolation keyword *(a10)*		Upstream contributing factor *(f10.2)*		Downstream contributing factor *(f10.2)*	
4	dx (distance to next iSIS node in the iSISMOD control file) *(f10.2)*							
5	ncells (number of aquifer cells interacting with a single River node) *(i4)*							
6	iSIS label *(a10)*	Layer index *(i4)*	Row Index *(i4)*	Column index *(i4)*	Segment number *(i4)*	Reach number *(i4)*	Hydraulic conductivity *(f15.10)*	Ground level *(f10.5)*
6+ncells	iSIS label *(a10)*	Layer index *(i4)*	Row Index *(i4)*	Column index *(i4)*	Segment number *(i4)*	Reach number *(i4)*	Hydraulic conductivity *(f15.10)*	Ground level *(f10.5)*
6+ncells+1	END (keyword required to indicate that the control file ends at that line)							

Table B.2: iSISMOD control file for River-Aquifer interaction

Line	Column							
	1	2	3	4	5	6	7	8
1	Header							
2	Header							
3	Keyword (describes the type of iSIS unit to interact to; i.e. RESERVOIR) *(a10)*							
4	ncells (number of aquifer cells interacting with a single Reservoir node) *(i4)*							
5	iSIS label *(a10)*	Layer index *(i4)*	Row Index *(i4)*	Column index *(i4)*	Segment number *(i4)*	Reach number *(i4)*	Hydraulic conductivity *(f15.10)*	Ground level *(f10.5)*
5+ncells	iSIS label *(a10)*	Layer index *(i4)*	Row Index *(i4)*	Column index *(i4)*	Segment number *(i4)*	Reach number *(i4)*	Hydraulic conductivity *(f15.10)*	Ground level *(f10.5)*
5+ncells+1	END (keyword required to indicate that the control file ends at that line)							

Table B.3: iSISMOD control file for Reservoir-Aquifer interaction

Where,

iSIS label label of the node that will interact will the aquifer cells specified below.

Layer index layer number of each of the aquifer cells (i).

Row index	row number of each of the aquifer cells (j).
Column index	column number of each of the aquifer cells (k).
Segment number	NOT USED. Column created if the GMS-MODFLOW interface is used with the Stream package.
Reach number	NOT USED. Column created if the GMS-MODFLOW interface is used with the Stream package.
Hydraulic conductivity	Vertical hydraulic leakage of the individual cell, expressed as the hydraulic conductivity divided by streambed thickness (L/T/L). **Time unit must be seconds.**
Ground level	Ground level of the individual cell (L).
Interpolation index	-1: means that interpolation between two successive iSIS nodes is required. Hydraulic leakage and ground levels are interpolated, whereas the aquifer map (layer, row and column indexes) are completed automatically between the iSIS nodes. 0: means that interpolation is not required.
Interpolation keyword	ROW: means that interpolation is performed along a row axis. COLUMN: means that interpolation is performed along a column axis.
Upstream contributing factor	factor (0-1) that defines the number of cells that contribute to the river reach defined between this iSIS node and the iSIS node located upstream.
Downstream contributing factor	factor (0-1) that defines the number of cells that contribute to the river reach defined between this iSIS node and the iSIS node located downstream.

A

```
Control file for isis-modflow interaction
isis_node_label layer row col segment reach
RIVER
0         ROW        0.0        1.0
25
400.0
node1     1    1    1  1    1    0.0100000000   5.000
node1     1    1    2  1    2    0.0100000000   5.000
node1     1    1    3  1    3    0.0100000000   5.000
node1     1    1    4  1    4    0.0100000000   5.000
node1     1    1    5  1    5    0.0100000000   5.000
node1     1    2    1  1    6    0.0100000000   5.000
node1     1    2    2  1    7    0.0100000000   5.000
node1     1    2    3  1    8    0.0100000000   5.000
node1     1    2    4  1    9    0.0100000000   5.000
node1     1    2    5  1    10   0.0100000000   5.000
node1     1    3    1  1    11   0.0100000000   5.000
node1     1    3    2  1    12   0.0100000000   5.000
node1     1    3    3  1    13   0.0100000000   5.000
node1     1    3    4  1    14   0.0100000000   5.000
node1     1    3    5  1    15   0.0100000000   5.000
node1     1    4    1  1    16   0.0100000000   5.000
node1     1    4    2  1    17   0.0100000000   5.000
node1     1    4    3  1    18   0.0100000000   5.000
node1     1    4    4  1    19   0.0100000000   5.000
node1     1    4    5  1    20   0.0100000000   5.000
node1     1    5    1  1    21   0.0100000000   5.000
node1     1    5    2  1    22   0.0100000000   5.000
node1     1    5    3  1    23   0.0100000000   5.000
node1     1    5    4  1    24   0.0100000000   5.000
node1     1    5    5  1    25   0.0100000000   5.000
RIVER
0         ROW        1.0        0.0
9
0.0
node2     1    2    6  1    1    0.0010000000   5.000
node2     1    2    7  1    2    0.0010000000   5.000
node2     1    2    8  1    3    0.0010000000   5.000
node2     1    3    6  1    4    0.0010000000   5.000
node2     1    3    7  1    5    0.0010000000   5.000
node2     1    3    8  1    6    0.0010000000   5.000
node2     1    4    6  1    7    0.0010000000   5.000
node2     1    4    7  1    8    0.0010000000   5.000
node2     1    4    8  1    9    0.0010000000   5.000
END
```

B

```
Control file for isis-modflow interaction
isis_node_label layer row col segment reach (kv/h) % F1
RESERVOIR
594
qtrain1   1    1    1  1     1   0.01       100.0
qtrain1   1    1    2  1     2   0.02       100.0
qtrain1   1    1    3  1     3   0.03       100.0
qtrain1   1    1    4  1     4   0.04       100.0
qtrain1   1    1    5  1     5   0.05       100.0
qtrain1   1    1    6  1     6   0.06       100.0
qtrain1   1    1    7  1     7   0.07       100.0
qtrain1   1    1    8  1     8   0.08       100.0
qtrain1   1    1    9  1     9   0.09       100.
qtrain1   1    2    1  1    10   0.010      99.5
qtrain1   1    2    2  1    11   0.011      99.5
qtrain1   1    2    3  1    12   0.012      99.5
qtrain1   1    2    4  1    13   0.013      99.5
qtrain1   1    2    5  1    14   0.014      99.5
qtrain1   1    2    6  1    15   0.015      99.5
qtrain1   1    2    7  1    16   0.016      99.5
qtrain1   1    2    8  1    17   0.017      99.5
qtrain1   1    2    9  1    18   0.018      99.5
qtrain1   1    3    1  1    19   0.019      99.
qtrain1   1    3    2  1    20   0.020      99.
qtrain1   1    3    3  1    21   0.021      99.
qtrain1   1    3    4  1    22   0.022      99.
qtrain1   1    3    5  1    23   0.023      99.
qtrain1   1    3    6  1    24   0.024      99.
qtrain1   1    3    7  1    25   0.025      99.
qtrain1   1    3    8  1    26   0.026      99.
qtrain1   1    3    9  1    27   0.027      99.
qtrain1   1    4    1  1    28   0.028      98.5
```

Figure B.3: A: iSISMOD Sample Control File for River-Aquifer interaction ("filename.mfl")
B: iSISMOD Sample Control File for Reservoir-Aquifer interaction ("filename.mfl")

B.4 Testing of iSISMOD

B.4.1 Test case 1

B.4.1.1 Objective and description

This test case aims at verifying the ability of the program to simulate interaction between an open surface body (simulated by iSIS using a reservoir unit) and an aquifer. The results obtained were checked against hand calculations.

The iSIS data file contained a single-node reservoir with a constant stage-area curve.

Two set of control files were used: one with a single aquifer cell interacting with the reservoir **(simulation 1A)** and another one with multiple cells interacting to the reservoir **(simulation 1B)**.

B.4.1.2 Results

Results were compared in two different ways:

(i) a two-layer MODFLOW model was set up. The top layer (unconfined) was defined to represent an open surface with a specific yield equal to one. The bottom layer was defined with zero hydraulic conductivity to simulate the vertical movement of water due to constant recharge rate. The grid was set to 9 square cells of 83m. The leakage for the reservoir bed was set to 0.01m/day per metre of streambed thickness.

(ii) a spreadsheet calculation was carried out to calculate the groundwater heads by solving the simplified equations for the vertical movement of water.

Figure B.4 and Table B.4 show the various outputs obtained from the simulations:

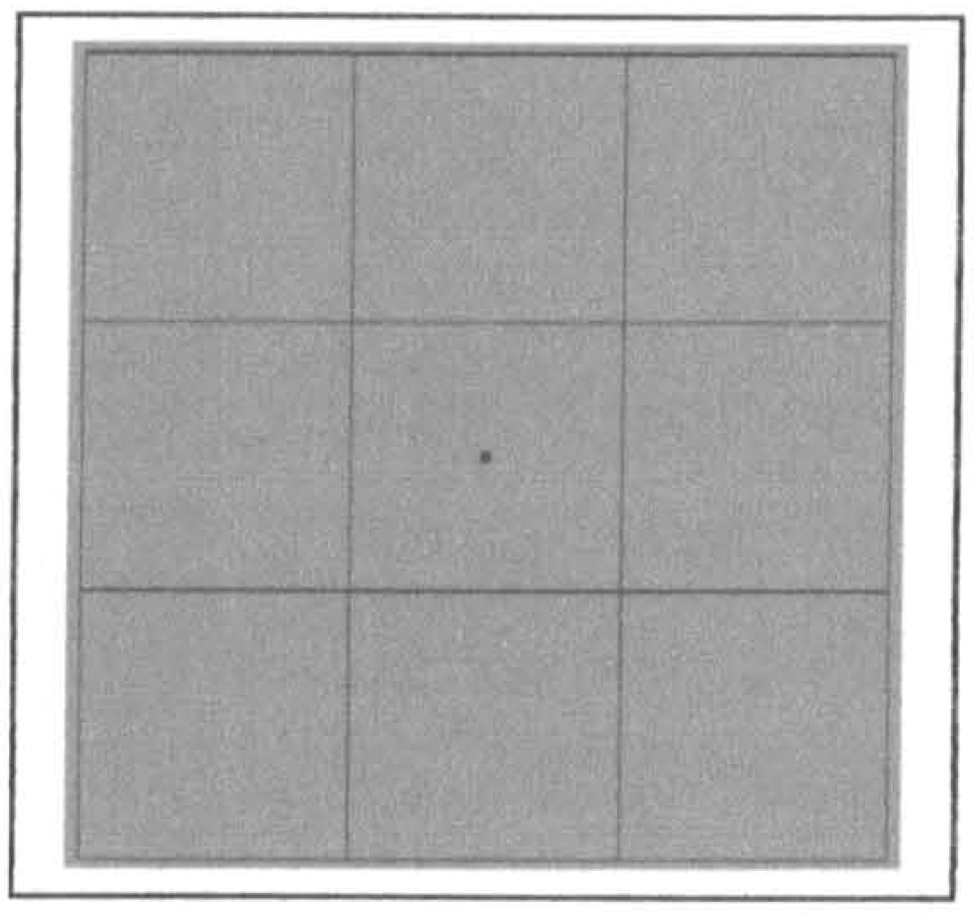


Figure B.4A: MODFLOW schematic, with the iSIS node (red dot) located in the centre cell (row=3, column=3)

```
          CUMULATIVE VOLUMES      L**3
          ------------------

             IN:
             ---
                  STORAGE =    0.00000E+00
            CONSTANT HEAD =    0.00000E+00
                 RECHARGE =    0.11250E+06
          ISIS    LEAKAGE =    0.00000E+00
                 TOTAL IN =    0.11250E+06
            OUT:
            ----
                  STORAGE =      61724.
            CONSTANT HEAD =    0.00000E+00
                 RECHARGE =    0.00000E+00
          ISIS    LEAKAGE =      50774.
                TOTAL OUT =    0.11250E+06
                 IN - OUT =      1.0547
      PERCENT DISCREPANCY =                  0.00
```

A

```
          CUMULATIVE VOLUMES      L**3
          ------------------

             IN:
             ---
                  STORAGE =    0.00000E+00
            CONSTANT HEAD =    0.00000E+00
                 RECHARGE =    0.11250E+06
          ISIS    LEAKAGE =    0.00000E+00
                 TOTAL IN =    0.11250E+06
            OUT:
            ----
                  STORAGE =    0.10392E+06
            CONSTANT HEAD =    0.00000E+00
                 RECHARGE =    0.00000E+00
          ISIS    LEAKAGE =      8583.2
                TOTAL OUT =    0.11250E+06
                 IN - OUT =      1.1406
      PERCENT DISCREPANCY =                  0.00
```

B

Figure B.4B: closure of the internal MODFLOW mass balance (captured from the MODFLOW output file "filename.out"). A: simulation 1A and B: simulation 1B.

	Simulation 1A	**Simulation 1B**
Leakage as presented in MODFLOW balance (m^3)	**50774**	**8583**
Water level in the reservoir at time 0 (m)	98.7	98.7
Water level in the reservoir at end of simulation (m)	105.94	99.89
Area of reservoir (m^2)	6944.45	6944.45
Change in Storage (m^3)	**50277**	**8264**
Discrepancy (%)	**0.98**	**3.79**

Table B.4: closure of the iSIS mass balance, taking into account leakage.

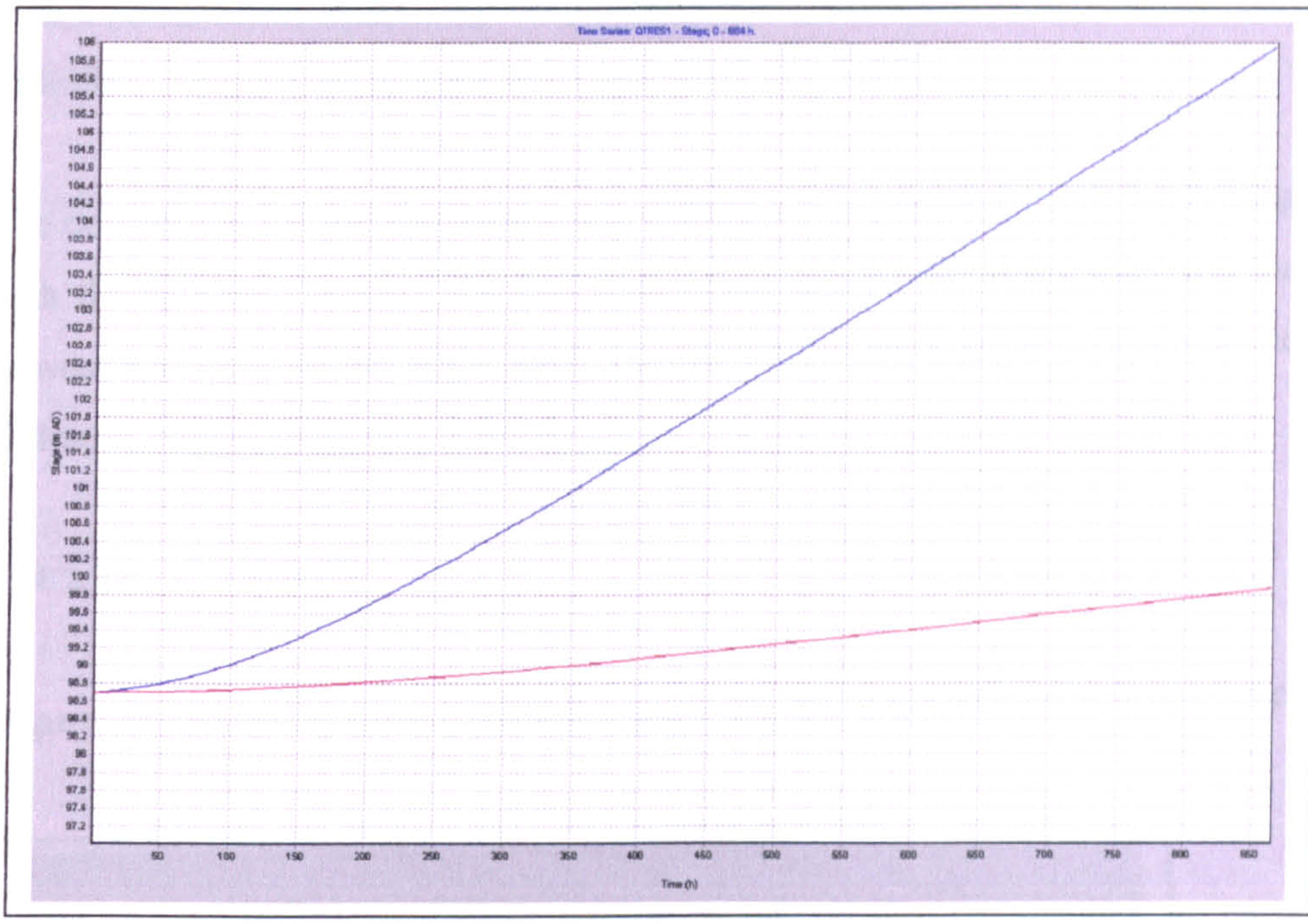


Figure B.4C: time series plot of head in the reservoir for both simulations, illustrating how the model reaches a higher level when the interaction takes place with all the MODFLOW cells. Variation of head for simulation 1B is shown in red. Variation of head for simulation 1A is shown in blue.

The water level at the end of each run compared satisfactorily to results obtained from the hand calculations.

B.4.2 Test case 2

B.4.2.1 Objective and description

This test case aims at verifying the capability of the program to simulate interaction between a reach of river channel (simulated by iSIS using a river unit) and an aquifer, under steady state conditions.

The iSIS data file consisted of a river reach of rectangular cross section, with a constant flow boundary at the upstream end and a rating curve at the downstream end.

A single layer MODFLOW file was set up with all cells defined as constant head boundaries in order to force a steady state solution from the interaction with iSIS. No external stresses were defined in the aquifer.

The control file for the simulation was defined with a set of 25 cells interacting with the upstream node of the first river reach and 9 cells interacting with the downstream node of the same reach. For the downstream set of cells a reduced hydraulic conductivity was defined.

B.4.2.2 Results

Figures B.5A and B.5B and Table B.5 show the set of outputs for this test case.

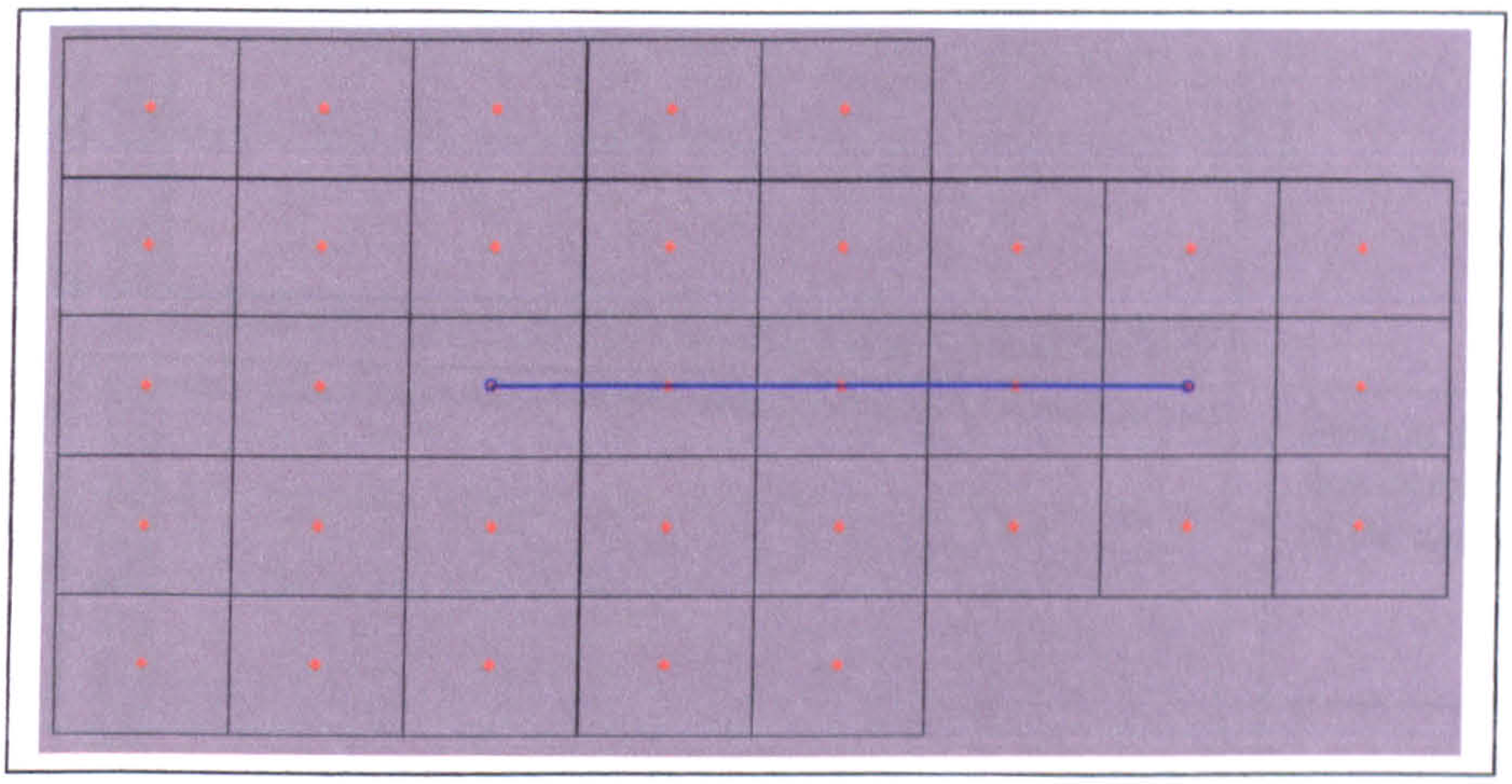


Figure B.5a: illustrates the schematic with the MODFLOW grid and the river channel. The red dots in each cell indicate that a constant head boundary was used.

A mass balance comparison was carried out in order to prove that, when the steady state is reached, the difference in flow entering and leaving the system equals the amount of leakage entering from the aquifer. Table B.5 presents the results obtained from the calculation.

Flow entering the channel (m^3/s)	150
Flow leaving the channel (m^3/s)	185
Leakage into the channel (m^3/s) **(calculated as total leakage volume divided by total length of time)**	35 (volume is $3,053,500m^3$)

Table B.5: Mass balance calculation.

Figure B.5b shows the variation of flow with time for the upstream and

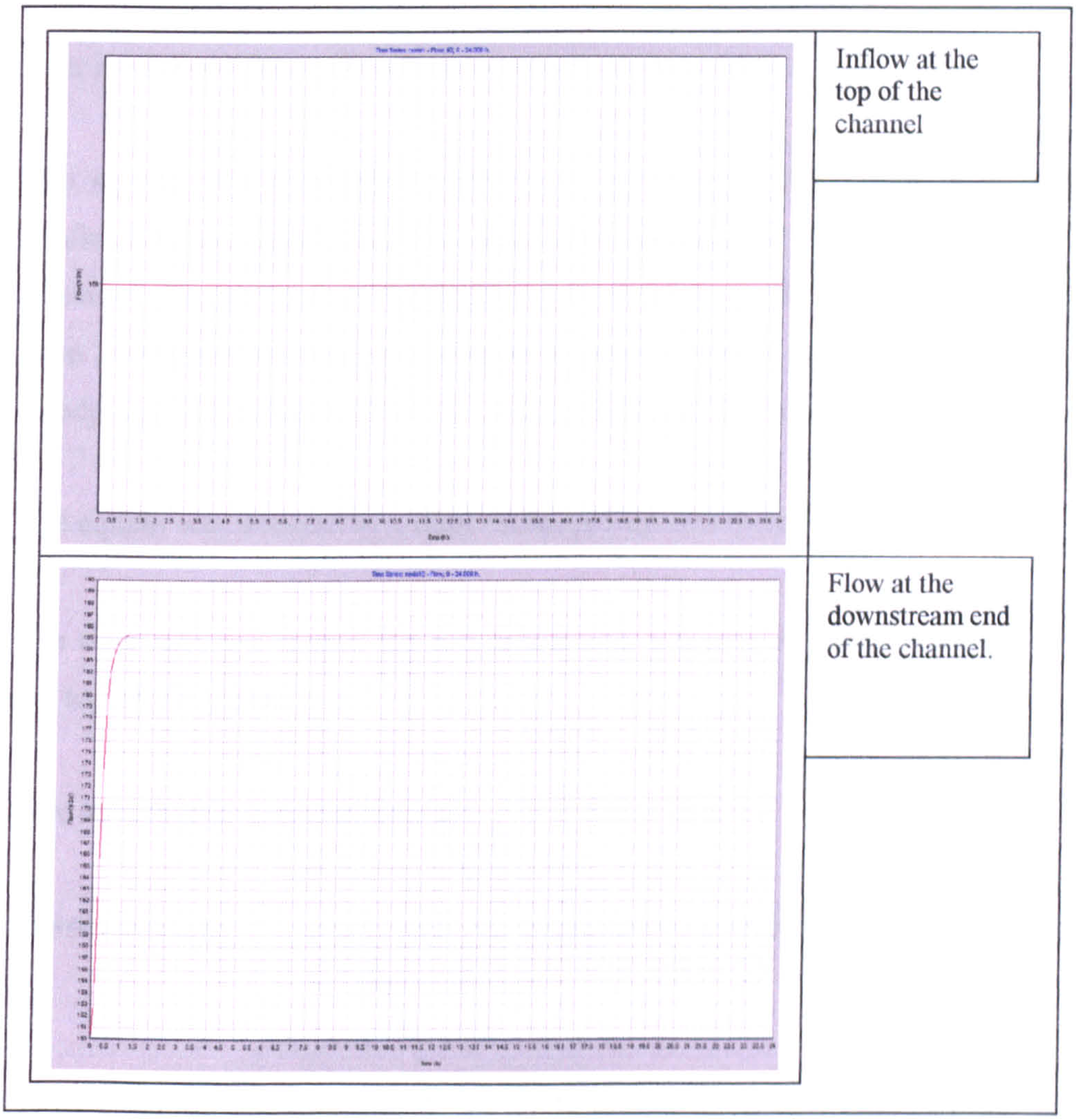


Figure B.5b: Flow-time hydrographs at the beginning and end of the river channel simulated with iSISMOD.

B.4.3 Test case 3

B.4.3.1 Objective and description

This test case aims at verifying the capability of the program to simulate interaction of a more complex channel network with an underlying aquifer. The channel network is comprised of a reservoir, linked via a spill unit to a river defined by a set of extended cross sections to represent the floodplain. The river is 32.5km long, and each cross section is approximately 4.5km wide.

The aquifer was schematised with two vertical layers (the lower one being confined by the upper one) and each layer was divided into 66 rows and 40 columns. The grid size of the aquifer was set as a variable row width, varying from 25m (corresponding to the main channel) to 500m (corresponding to the floodplain). The column width was a constant value of 500m.

The aquifer was stressed by a daily recharge rate of 0.20m/day.

The river network started the simulation with a constant baseflow of $1m^3/s$ at the top of the channel.

Two simulations were carried out:

Simulation 3A: where only the interaction between the reservoir and the aquifer is allowed.

Simulation 3B: the interaction takes place between the reservoir and the river system.

The objective of splitting the test case in two simulations was to determine the leakage that enters the reservoir and the river separately, in order to perform a water balance for the reservoir and for the river independently.

B.4.3.2 Results

Figures B.6 to B.8 and Tables B.6 and B.7 show the various outputs obtained from the simulation.

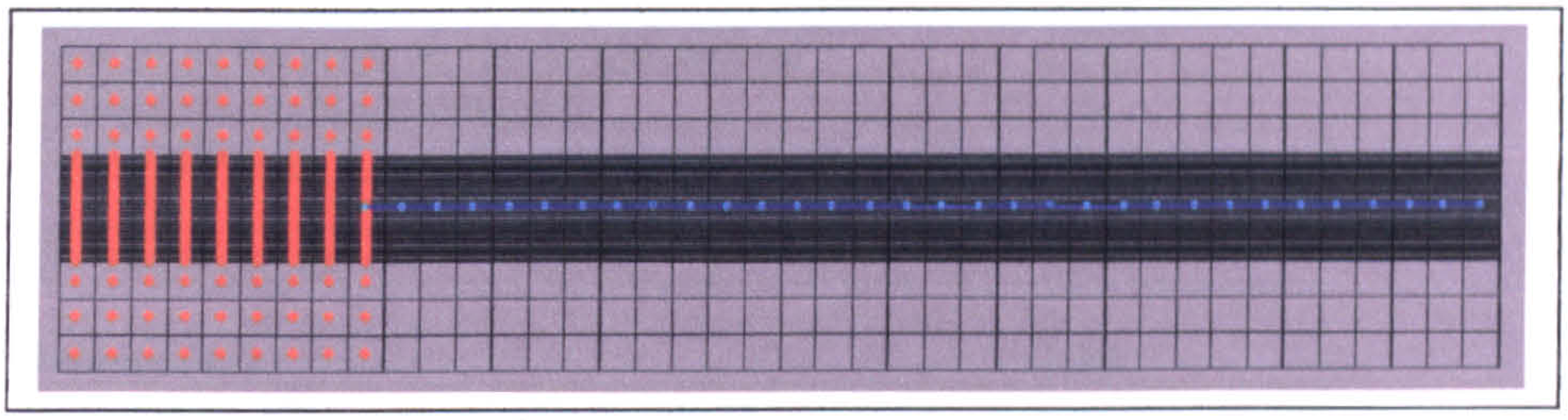


Figure B.6: Schematic of model. The red dots indicate all the cells that interact with the reservoir node, whereas the blue segments denote the river channels.

Tables B.6 and B.7 summarise the mass balance calculated for the entire model.

B.4.3.2.1 Simulation 3A

Aquifer (values in millions of m^3)

```
CUMULATIVE VOLUMES        L**3
------------------

        IN:
        ---
           STORAGE =    0.85513E+06
     CONSTANT HEAD =    0.00000E+00
          RECHARGE =    0.54000E+09
    ISIS   LEAKAGE =    0.00000E+00
          TOTAL IN =    0.54086E+09
       OUT:
       ----
           STORAGE =    0.44085E+09
     CONSTANT HEAD =    0.00000E+00
          RECHARGE =    0.00000E+00
    ISIS   LEAKAGE =    0.99993E+08
         TOTAL OUT =    0.54084E+09
          IN - OUT =     11776.
PERCENT DISCREPANCY =                 0.00
```

Open channel network (values in millions of m^3)

Flow entering the reservoir (m^3)	0
Leakage into the reservoir (m^3)	100.0
Total inflow (m^3)	**100.0**
Flow out of the reservoir via the spill unit (m^3)	64.8
Leakage out of the reservoir (m^3)	0
Total outflow (m^3)	**64.8**
Change in storage (m^3) – reservoir	**38.6**
Balance (m^3)	**3.4**
Discrepancy (%)	**3.4%**

Table B.6: Mass balance calculation. Above: for the aquifer, extracted from MODFLOW. Below: for the reservoir calculated manually using relevant output from iSIS.

B.4.3.2.2 Simulation 3B

Aquifer (values in millions of m^3)

```
        CUMULATIVE VOLUMES        L**3
        ------------------

              IN:
              ---
                STORAGE =     0.77099E+06
          CONSTANT HEAD =     0.00000E+00
               RECHARGE =     0.54000E+09
        ISIS    LEAKAGE =     0.00000E+00
               TOTAL IN =     0.54077E+09
             OUT:
             ----
                STORAGE =     0.25434E+09
          CONSTANT HEAD =     0.00000E+00
               RECHARGE =     0.00000E+00
        ISIS    LEAKAGE =     0.28644E+09
              TOTAL OUT =     0.54078E+09
               IN - OUT =     -4800.0
    PERCENT DISCREPANCY =                    0.00
```

Open channel network (values in millions of m^3)

Flow entering the river via the spill unit (m^3)	64.8
Total leakage into reservoir and river (m^3)	(286.4)
Constant Baseflow (m^3)	2.6
Leakage entering the river system (m^3)	186.4
Total inflow (m^3)	**253.8**
Leakage out of the river (m^3)	0
Flow out of the river system (m^3)	229.5
Total outflow (m^3)	**229.5**
Change in storage (m^3) – river	**20**
Balance (m^3)	**-4.3**
Discrepancy (%)	**1.7**

Table B.7: Mass balance calculation. Above: for the aquifer, extracted from MODFLOW. Below: for the river calculated manually using relevant output from iSIS.

Figure B.7 shows the variation of head and flow in key locations of the system, whereas figure B.8 presents the maximum and minimum level in a cross section of the system, as the leakage from the aquifer enters into it.

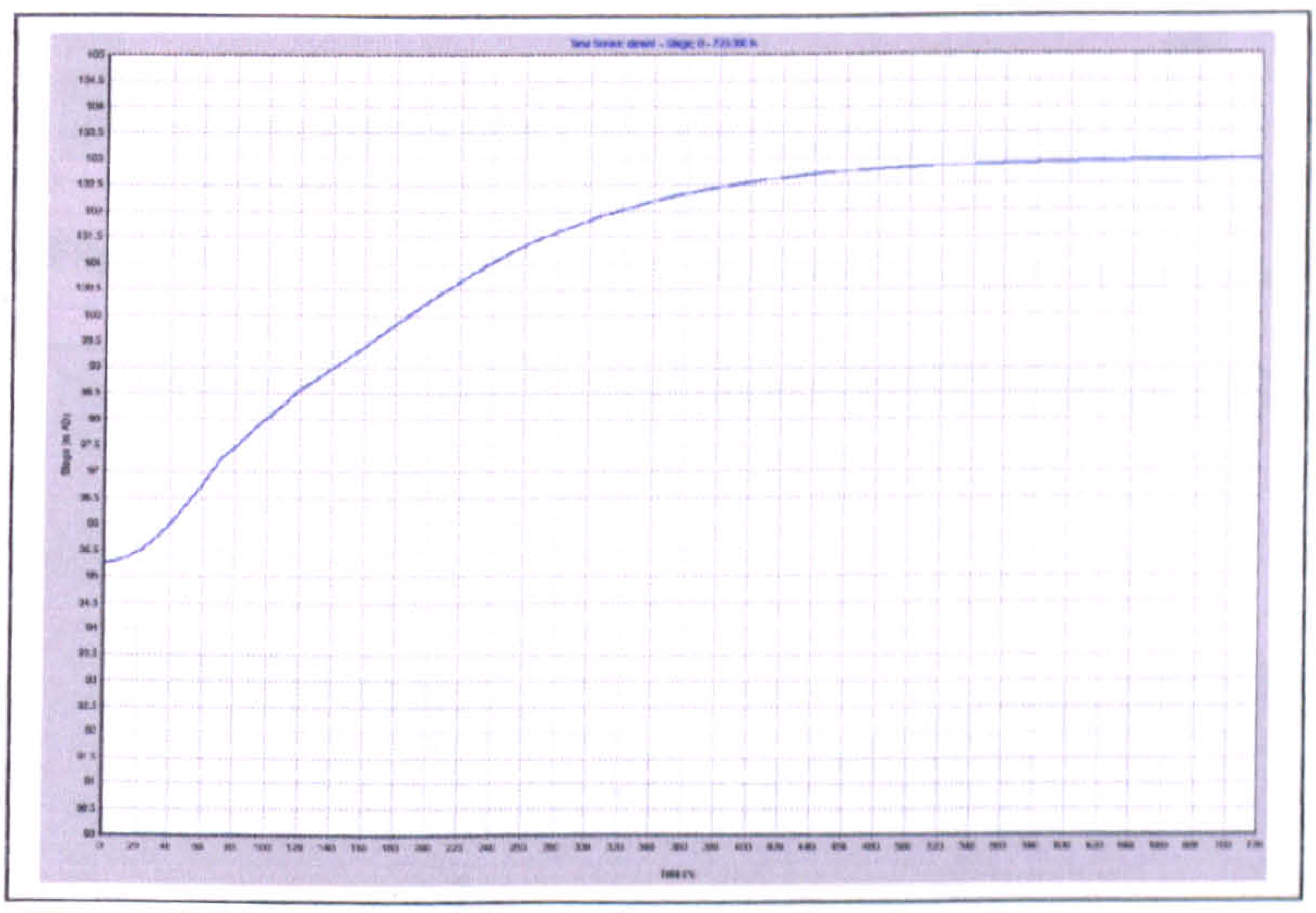


Figure B.7A: Stage-Time in the reservoir unit.

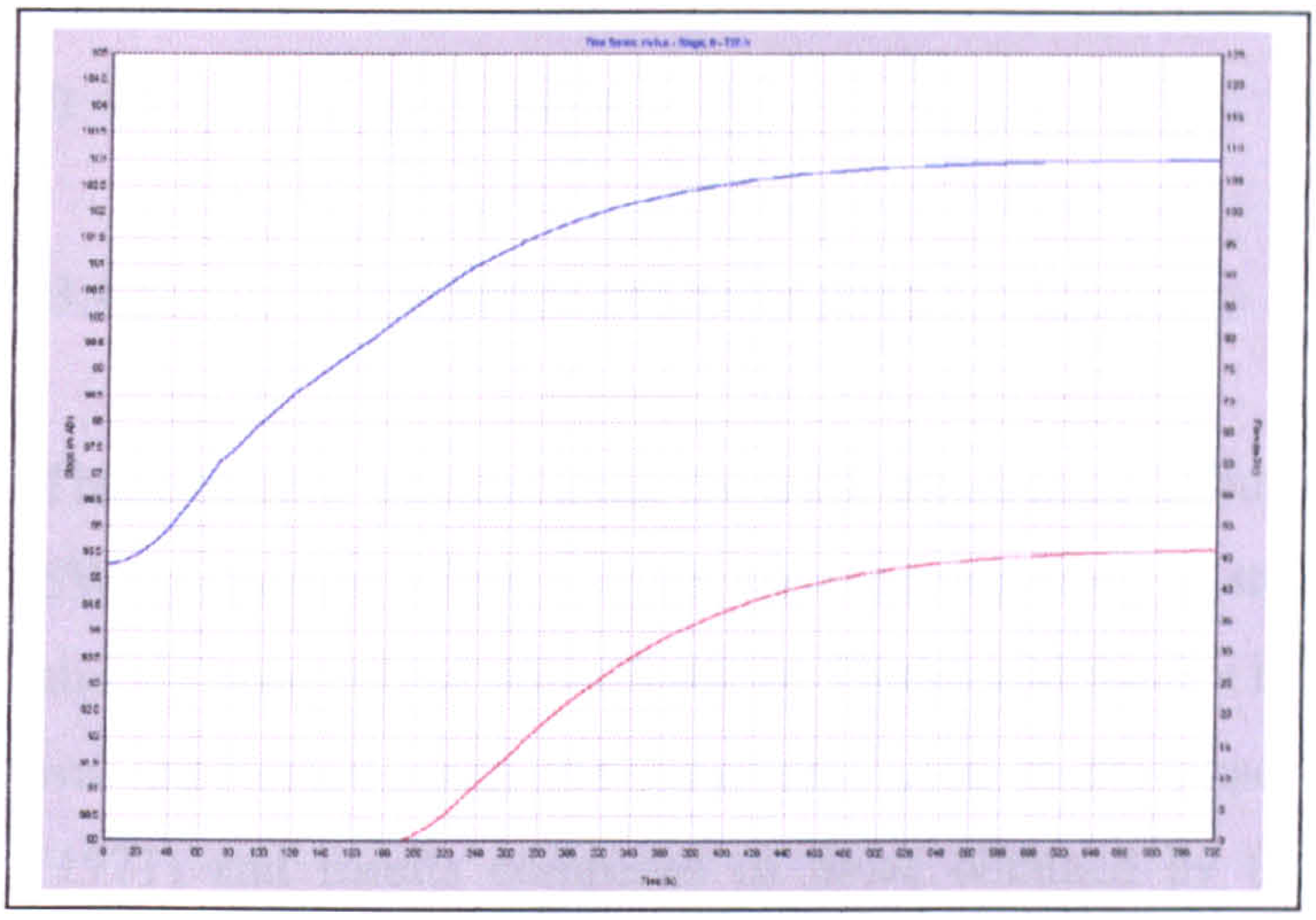


Figure B.7B: Stage-Time (blue) and Flow-Time (red) in the spill unit.

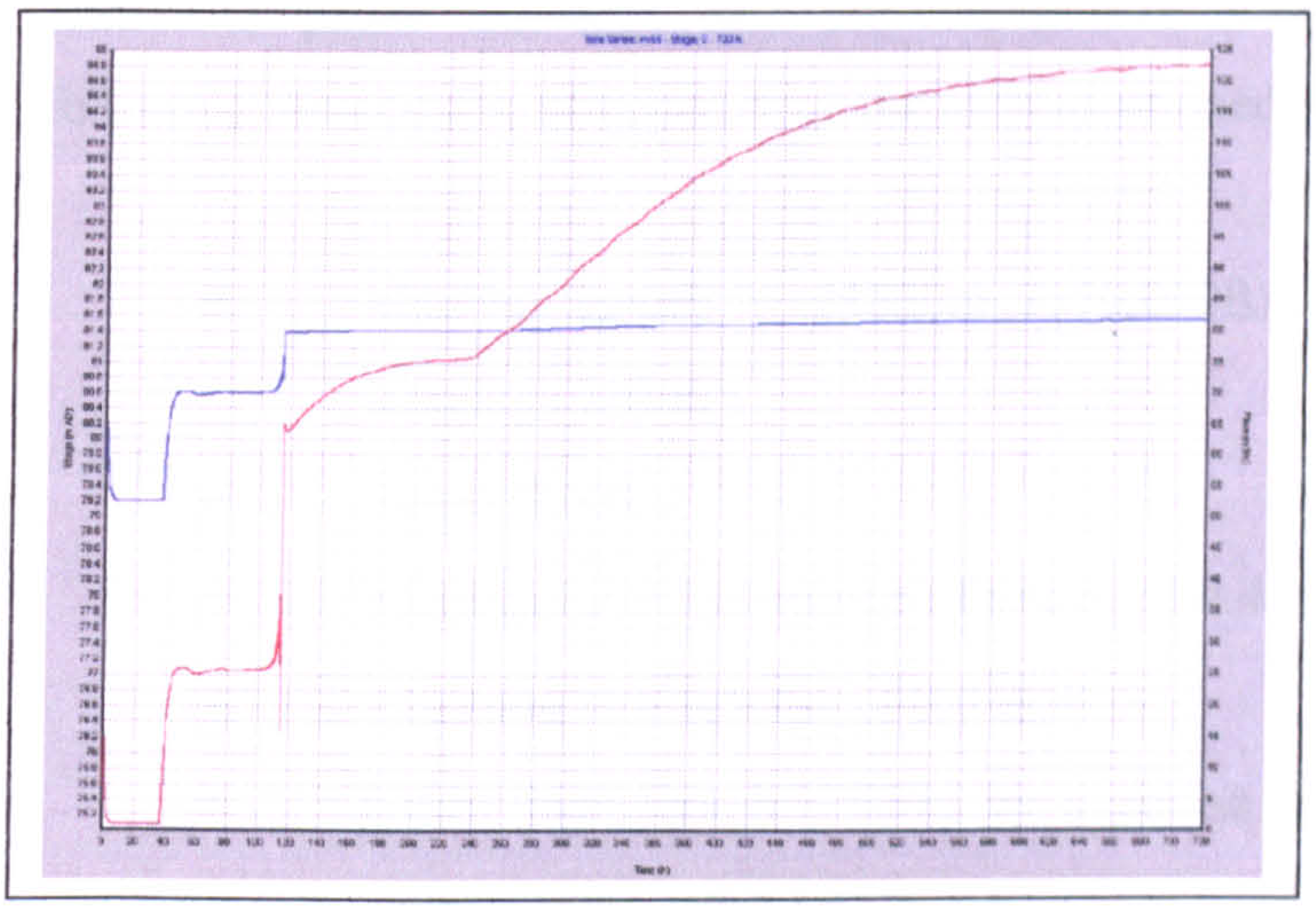


Figure B.7C: Stage-Time (blue) and Flow-Time (red) at the end of river channel.

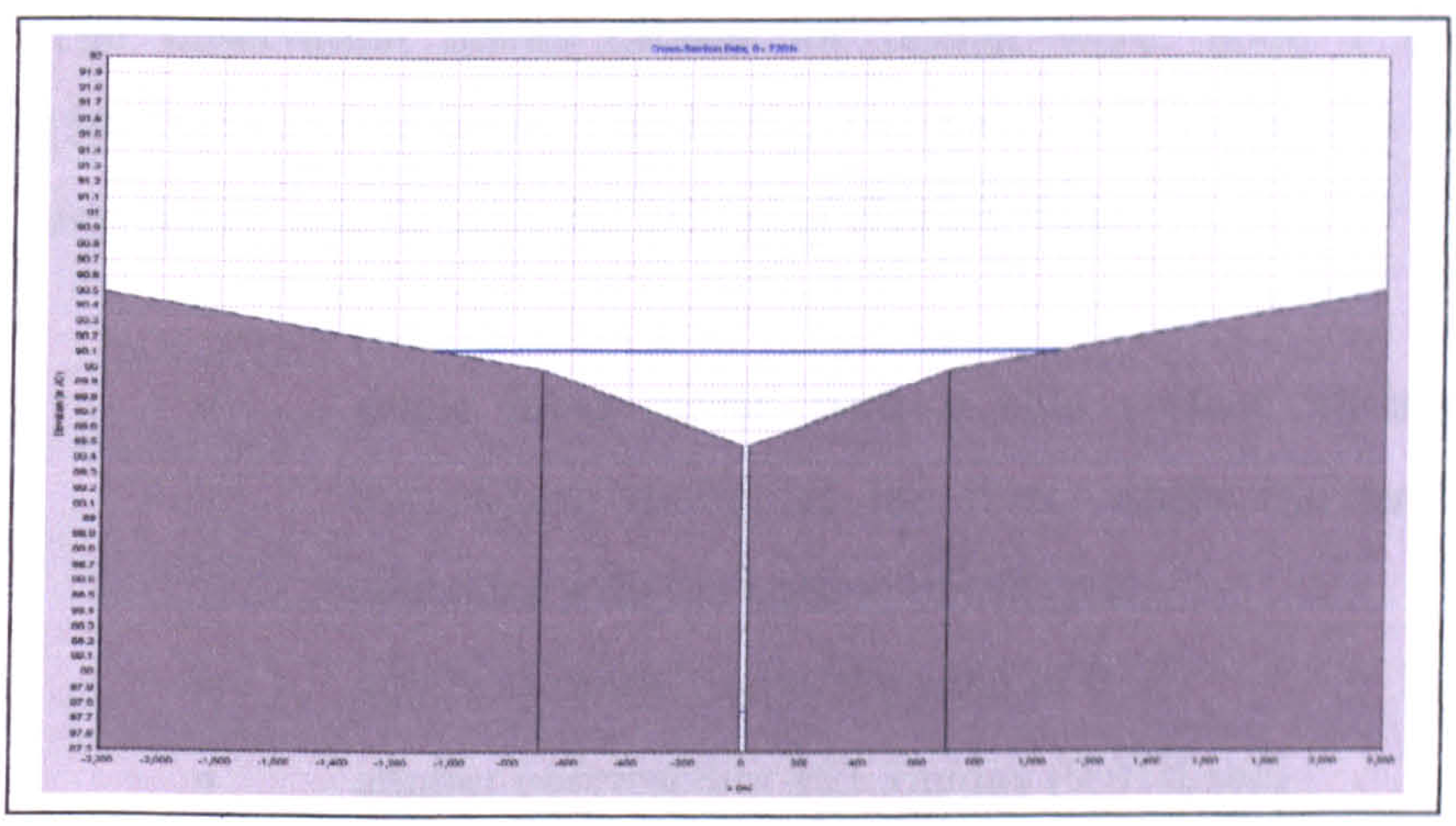


Figure B.8: Extended cross section of the river, showing the minimum and maximum water level achieved due to the leakage entering from the aquifer.

B.4.4 Test case 4

B.4.4.1 Objective and description

This test aims at simulating the bank attenuation effect that results from GW-SW interaction when a flood wave passes along a stream. This exercise has already been solved numerically by Pinder and Sauer (1971). An iSISMOD run was performed using the same data used in the paper by Pinder and Sauer (1971) and results compared to those obtained by those authors. Data are expressed in the original units used by Pinder and Sauer (feet) for consistency with their paper. The iSIS data file consisted of a single channel with the following dimensions, obtained from the aforementioned paper:

- channel length = 51850m (170,000ft) with nodes at 610m spacing (2000ft)
- slope=0.001
- rectangular cross section of width = 30.48m (100ft)
- Manning's roughness of 0.03858
- inflow hydrograph defined by a cosine function with an initial value of 510 cumecs.

The observation points chosen for testing were: node 1 (0ft), node 25 (50,000ft) and node 70 (140,000ft). The MODFLOW data file consisted of an unconfined aquifer with the following characteristics:

- single layer model with a land surface elevation of 305m everywhere except at the river, where the surface elevation coincides with the bottom of the river.
- aquifer storativity/specific yield of 0.25.
- aquifer permeability 263.3m/day (0.01ft/sec).

- grid dimensions: vertical spacing of 610m (in the direction of the stream), horizontal spacing of 30m everywhere except near either bank of the stream where the spacing was set at 15m.
- boundary conditions set to zero flow all around the aquifer.

B.4.4.2 Results

The importance of simulating SW-GW interaction to predict the attenuation due to banks storage effect when a flood wave passes along a stream was demonstrated by Pinder and Sauer (1971), and it was also satisfactorily reproduced by iSISMOD. Figures B.9 to B.11 and Table B.8 show the results of this test case.

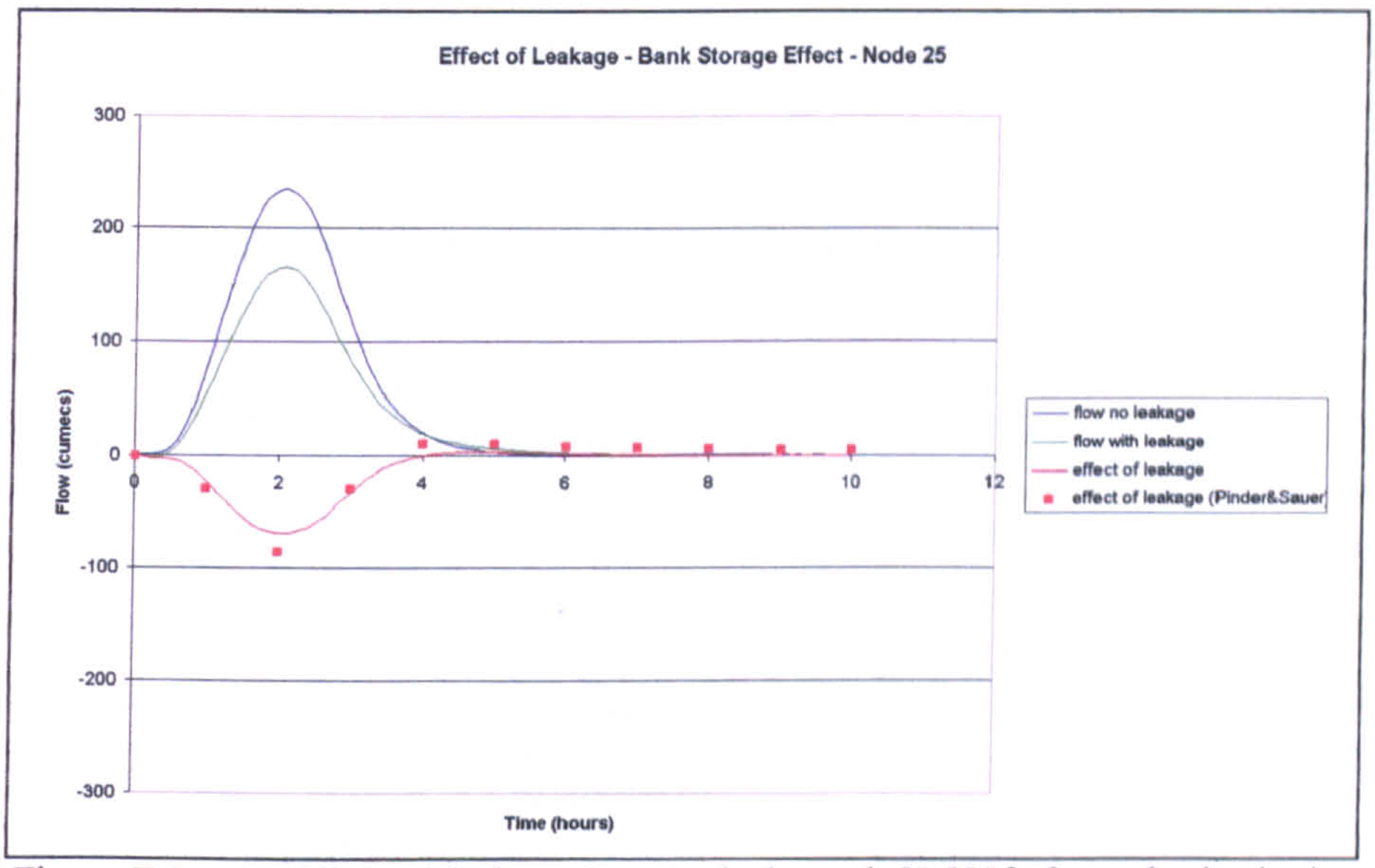


Figure B.9: Effect of leakage in a node located 50,000ft from the beginning of the channel.

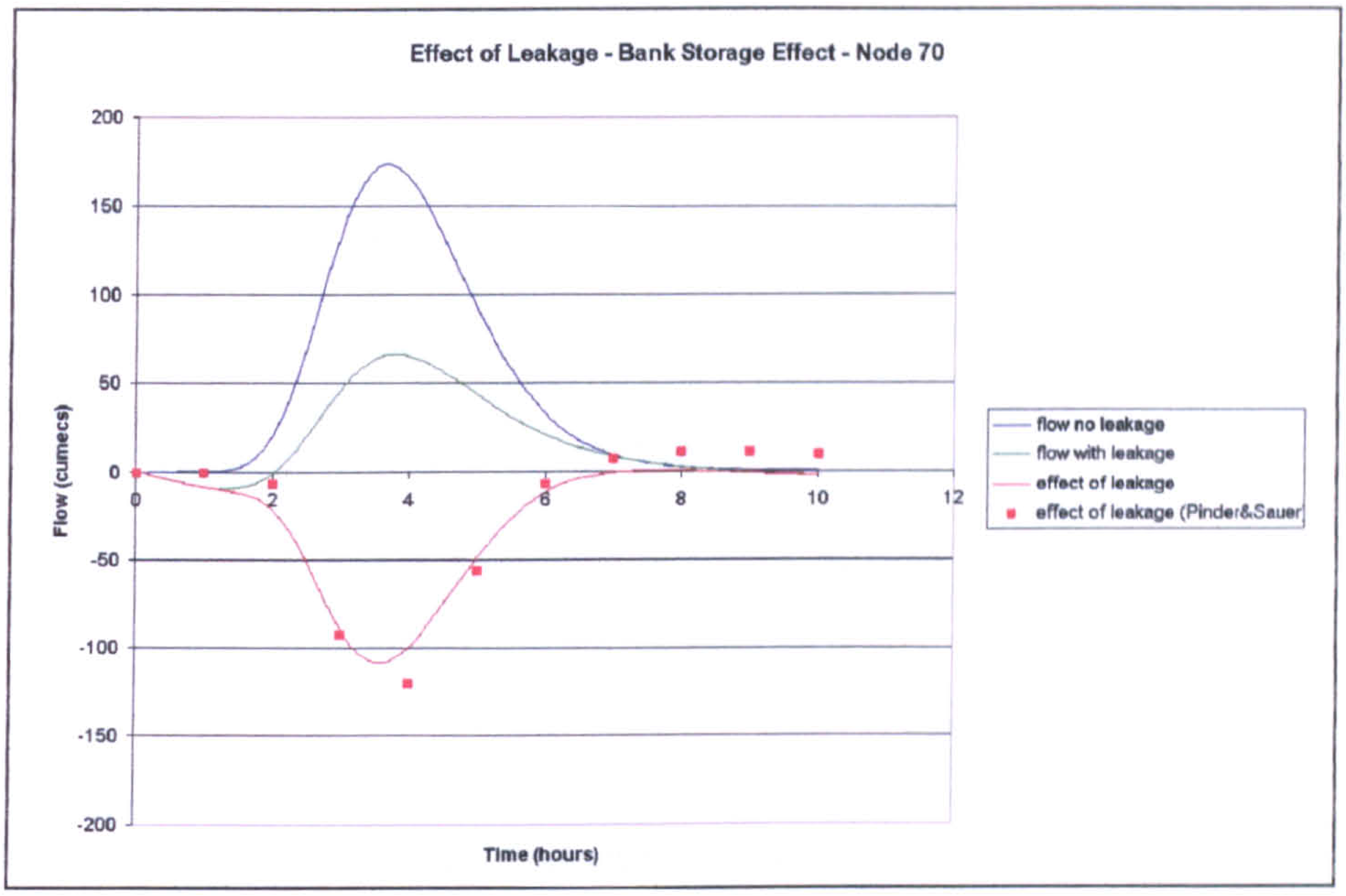


Figure B.10: Effect of leakage in a node located 140,000ft from the beginning of the channel.

Table B.8 summarises the mass balance along the river network.

Aquifer (values in millions of m^3)

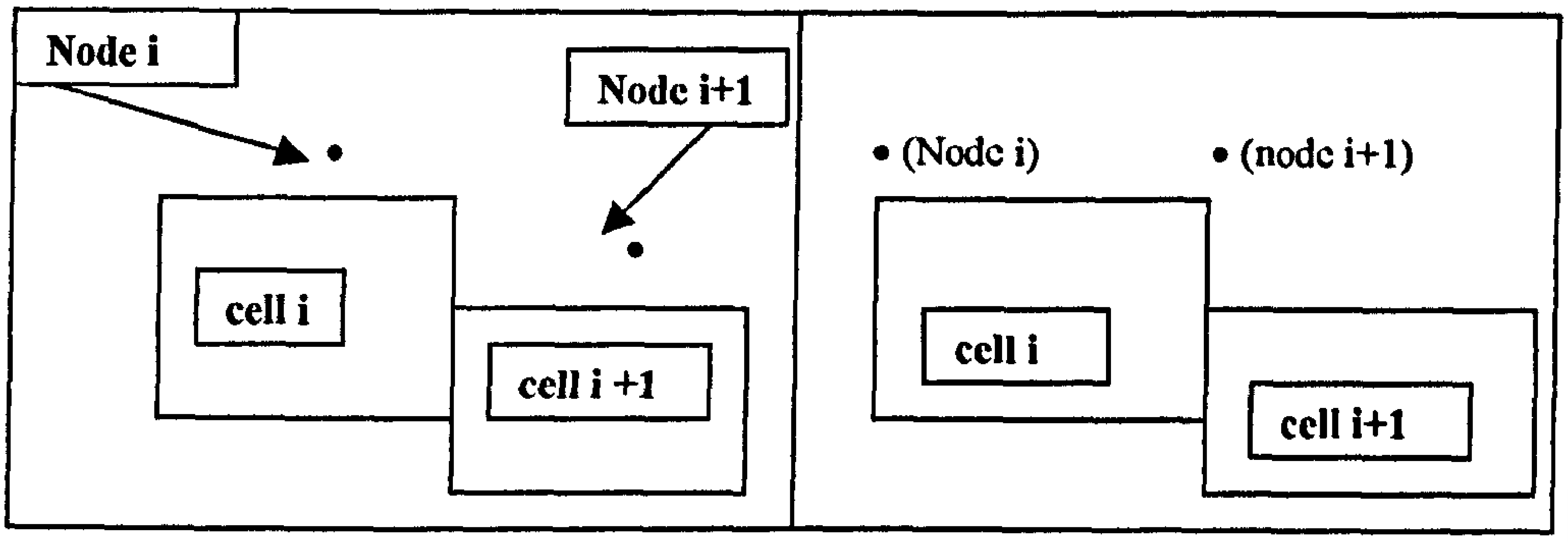
```
        CUMULATIVE VOLUMES        L**3
        ------------------

              IN:
              ---
                STORAGE =    0.34851E+06
          CONSTANT HEAD =    0.00000E+00
         ISIS   LEAKAGE =    0.10875E+07
               TOTAL IN =    0.14360E+07
             OUT:
             ----
                STORAGE =    0.14061E+07
          CONSTANT HEAD =    0.00000E+00
         ISIS   LEAKAGE =     29935.
              TOTAL OUT =    0.14360E+07
               IN - OUT =    0.12500
    PERCENT DISCREPANCY =                     0.00
```

Open channel network (values in millions of m^3)

Flow entering the river channel (m^3)	19.98
Leakage into the river (m^3)	0.03
Total inflow (m^3)	**20.01**
Flow out of the river channel (m^3)	19.0
Leakage out of the river (m^3)	1.09
Total outflow (m^3)	**20.09**
Change in storage (m^3)	**-0.014**
Balance (m^3)	**0.066**
Discrepancy (%)	**0.3%**

Table B.8: Mass balance calculation. Above: for the aquifer, extracted from MODFLOW. Below: for the river calculated manually using relevant output from iSIS.

Figures B.9 and B.10 show that there are some small differences between the results predicted by iSISMOD and those published in the paper. The documentation of the MODBRANCH program also included, as one of the two test cases, the same example of Pinder and Sauer (1971), showing a close agreement in the predicted leakage effect in the propagation of the flood wave. However MODBRANCH development uses a different approach for the schematization of the open channel and aquifer interaction, leading to a different formulation of the leakage expression of the continuity equation. The schematization used by MODBRANCH assumes that there is one river node at the beginning and end of each aquifer cell, which means that there is a single groundwater head interacting with each river reach. Figure B.11 compares both approaches.



iSISMOD Approach	MODBRANCH Approach
$Ql = \theta \times K \times (h_{i+1} - H_{i+1}) +$ $(1-\theta) \times K \times (h_i + H_i)$	$Ql = K \times \left[\frac{(h_{i+1} + h_i)}{2} - H_i \right]$

Figure B.11: Leakage calculation in iSISMOD and MODBRANCH. In both cases K is conductance.

The different approach used in iSISMOD, compared to the one used by MODBRANCH, results in a faster and larger contribution from the river to the aquifer at the beginning of the flood wave propagation that raises the groundwater heads more rapidly, decreasing the effect of leakage as the time passes.

Smaller differences could be expected when digitizing the results obtained by Pinder and Sauer (1971), and from the mathematical solver used by each open channel flow program: iSIS Flow and BRANCH.

B.4.5 Test case 5

B.4.5.1 Objective and description

The final test case was designed to test that the modifications made to the iSIS program did not affect the normal solution when the no coupling option is chosen. A complex data file from the Rio Salado Master Plan project was selected and run using iSISMOD. Results were compared with those obtained running iSIS Flow version 2.1.

B.4.5.2 Results

Figure B.12 shows a flow and a level hydrograph at two locations of the system, with no noticeable differences between the two solutions. It may be concluded that iSISMOD preserves the computational characteristics of the iSIS model when no interaction with groundwater occurs.

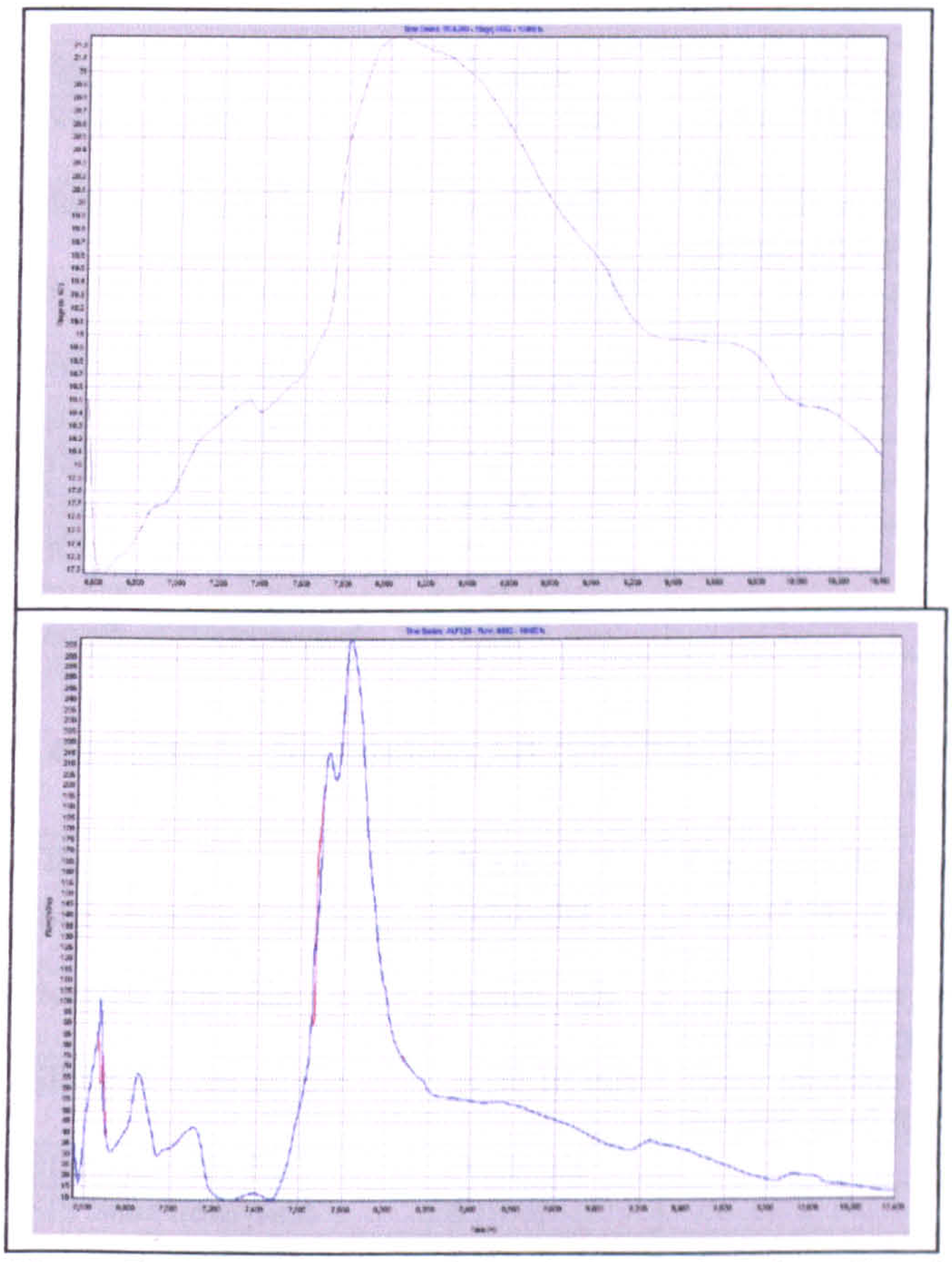


Figure B.12: Above: level-time hydrograph. Below: flow-time hydrograph.

- APPENDIX C -

RUN LOGS

Test Case 1 - Simulation 1A (iSISMOD)

File	Name	Comments
ISIS datafile	9cells.dat	Area of the reservoir is equal to the area of one cell
Modflow Superfile	9cells.mfs	The only stress included was recharge to the uppermost layer.
ISISMOD Control file	9cells1A.mfl	Only the centred cell is linked to the ISIS label for the reservoir.
ISISMOD Plot file	9cells.plt	
ISIS Start time (hrs)	0	
ISIS End Time (hrs)	864	
ISIS Time step (sec)	86400	
MODFLOW Stress periods	36	
Length of stress period	1day	

Test Case 1 - Simulation 1B (iSISMOD)

File	Name	Comments
ISIS datafile	9cells.dat	Area of the reservoir is equal to the area of one cell
Modflow Superfile	9cellsc.mfs	The only stress included was recharge to the uppermost layer.
ISISMOD Control file	9cells1B.mfl	The 9 Modflow cells of the top layer are linked to the ISIS label for the reservoir.
ISISMOD Plot file	9cells.plt	
ISIS Start time (hrs)	0	
ISIS End Time (hrs)	864	
ISIS Time step (sec)	86400	
MODFLOW Stress periods	36	
Length of stress period	1day	

Test Case 2 (iSISMOD)

File	Name	Comments
ISIS datafile	test6.dat	
Modflow Superfile	test5a.mfs	The only stress included was recharge to the uppermost layer.
ISISMOD Control file	test5.mfl	Modflow cells only interact to node 1 and node 2.
ISISMOD Plot file	test5.plt	
ISIS Start time (hrs)	0	
ISIS End Time (hrs)	24	
ISIS Time step (sec)	360	
MODFLOW Stress periods	24	
Length of stress period	1 hour	

Test Case 3 – Simulation 3A

File	Name	Comments
ISIS datafile	aqtest4r.dat	
Modflow Superfile	aqtest4.mfs	
ISISMOD Control file	aqtestr4.mfl	
ISISMOD Plot file	aqtest3.plt	
ISIS Start time (hrs)	0	
ISIS End Time (hrs)	720	
ISIS Time step (sec)	150	
MODFLOW Stress periods	30	
Length of stress period	1 day	

Test Case 3 – Simulation 3B (iSISMOD)

File	Name	Comments
ISIS datafile	aqtest4r.dat	
Modflow Superfile	aqtest4.mfs	
ISISMOD Control file	res.mfl	
ISISMOD Plot file	aqtest3.plt	
ISIS Start time (hrs)	0	
ISIS End Time (hrs)	720	
ISIS Time step (sec)	150	
MODFLOW Stress periods	30	
Length of stress period	1 day	

Test Case 4 (iSISMOD)

File	Name	Comments
ISIS datafile	Pinder_f.dat	
Modflow Superfile	Pinder_f.mfs	
ISISMOD Control file	Pinder_f.mfl	
ISISMOD Plot file	Pinder_f.plt	
ISIS Start time (hrs)	0	
ISIS End Time (hrs)	10	
ISIS Time step (sec)	300	
MODFLOW Stress periods	120	
Length of stress period	5 minutes	

Test Case 5 (iSISMOD)

File	Name	Comments
ISIS datafile	sal85_39.dat	File used to reproduce the calibration event of 1985 in the Rio Salado.
Modflow Superfile	not applicable	
ISISMOD Control file	not applicable	
ISISMOD Plot file	not applicable	
ISIS Start time (hrs)		
ISIS End Time (hrs)		
ISIS Time step (sec)	450	The adaptive time step option was used originally in the project. 450sec was the minimum time step used.
MODFLOW Stress periods	not applicable	
Length of stress period	not applicable	

Run 2 (iSISMOD)

File	Name	Comments
ISIS datafile	sw1infpar5.dat	Test area iSIS model
Modflow Superfile	run2.mfs	500m aquifer model with daily infiltration
ISISMOD Control file	run2.mfl	
ISISMOD Plot file	sections.plt	
ISIS Start time (hrs)	0	01/01/1996
ISIS End Time (hrs)	289272	31/12/2029
ISIS Time step (sec)	3600	saving every 24 time steps
MODFLOW Stress periods	12053	
Length of stress period	1 day	

Run 3 (iSISMOD)

File	Name	Comments
ISIS datafile	swlinfpar5.dat	Test area iSIS model
Modflow Superfile	run3.mfs	500m aquifer model with daily infiltration
ISISMOD Control file	run3.mfl	
ISISMOD Plot file	sections.plt	
ISIS Start time (hrs)	196520	02/06/1985
ISIS End Time (hrs)	236700	01/01/1990
ISIS Time step (sec)	3600	saving every 24 time steps
MODFLOW Stress periods	1675	
Length of stress period	1 day	

Run 5 (MODFLOW)

File	Name	Comments
ISIS datafile	-	
Modflow Superfile	run5.mfs	500m aquifer model with daily infiltration
ISISMOD Control file	-	
ISISMOD Plot file	-	
ISIS Start time (hrs)	-	02/06/1985
ISIS End Time (hrs)	-	01/01/1990
ISIS Time step (sec)	-	
MODFLOW Stress periods	1675	
Length of stress period	1 day	

Run 6 (iSISMOD)

File	Name	Comments
ISIS datafile	swlinfpar5.dat	Test area iSIS model
Modflow Superfile	run6.mfs	500m aquifer model with daily rainfall
ISISMOD Control file	run6.mfl	
ISISMOD Plot file	-	
ISIS Start time (hrs)	196520	02/06/1985
ISIS End Time (hrs)	236700	01/01/1990
ISIS Time step (sec)	3600	saving every 24 time steps
MODFLOW Stress periods	1675	
Length of stress period	1 day	

Run 7 (iSISMOD)

File	Name	Comments
ISIS datafile	sw1infpar5.dat	Test area iSIS model
Modflow Superfile	run7.mfs	500m aquifer model with daily rainfall
ISISMOD Control file	run7.mfl	
ISISMOD Plot file	sections.plt	
ISIS Start time (hrs)	0	01/01/1996
ISIS End Time (hrs)	289272	31/12/2029
ISIS Time step (sec)	3600	saving every 24 time steps
MODFLOW Stress periods	12053	
Length of stress period	1 day	

Run 11 (MODFLOW)

File	Name	Comments
ISIS datafile	-	
Modflow Superfile	run11.mfs	500m aquifer model with monthly infiltration
ISISMOD Control file	-	
ISISMOD Plot file	-	
ISIS Start time (hrs)	-	01/01/1963
ISIS End Time (hrs)	-	31/12/1995
ISIS Time step (sec)	-	
MODFLOW Stress periods	395	
Length of stress period	30.44 days	

Reg_cal (MODFLOW)

File	Name	Comments
ISIS datafile	-	
Modflow Superfile	5k-59.mfs	5000m aquifer model with monthly infiltration
ISISMOD Control file	-	
ISISMOD Plot file	-	
ISIS Start time (hrs)	-	01/01/1963
ISIS End Time (hrs)	-	31/12/1995
ISIS Time step (sec)	-	
MODFLOW Stress periods	395	
Length of stress period	30.44 days	

Reg_bas (MODFLOW)

File	Name	Comments
ISIS datafile	-	
Modflow Superfile	5k-60.mfs	5000m aquifer model with monthly infiltration
ISISMOD Control file	-	
ISISMOD Plot file	-	
ISIS Start time (hrs)	-	01/01/1996
ISIS End Time (hrs)	-	31/12/2029
ISIS Time step (sec)	-	
MODFLOW Stress periods	395	
Length of stress period	30.44 days	

RUN 8 (MODFLOW)

File	Name	Comments
ISIS datafile	-	
Modflow Superfile	run8.mfs	5000m aquifer model with monthly infiltration and 1.5m extinction depth instead of 3m
ISISMOD Control file	-	
ISISMOD Plot file	-	
ISIS Start time (hrs)	-	01/01/1963
ISIS End Time (hrs)	-	31/12/1995
ISIS Time step (sec)	-	
MODFLOW Stress periods	395	
Length of stress period	30.44 days	

RUN 9 (MODFLOW)

File	Name	Comments
ISIS datafile	-	
Modflow Superfile	run9.mfs	5000m aquifer model with monthly rainfall
ISISMOD Control file	-	
ISISMOD Plot file	-	
ISIS Start time (hrs)	-	01/01/1963
ISIS End Time (hrs)	-	31/12/1995
ISIS Time step (sec)	-	
MODFLOW Stress periods	395	
Length of stress period	30.44 days	

Notes:

(1) The extinction depth of the evapotranspiration module of the MODFLOW model was 3m.

(2) The potential evapotranspiration series consist of monthly values.

Flood Probability Maps (FPM)

Name of FPM (image file)	Description	Associated run
bfrmrda.img	5000m/baseline/monthly infiltration/basin	reg_bas
rmap_rc.img	5000m/calibration/monthly infiltration/basin	reg_cal
bfrmw.img	5000m/baseline/monthly infiltration/test area	reg_bas
rmap_rcw.img	5000m/calibration/monthly infiltration/test area	reg_cal
rmap_nc.img	500m/calibration/monthly infiltration/test area	run 11
run2.img	500m/baseline/daily infiltration/test area	run 2
run7.img	500m/baseline/daily rainfall/test area	run 7

- APPENDIX D -

HOW TO

D.1 Introduction

This appendix summarizes the key procedures that would be required to reproduce any of the results presented in the main body of this thesis. Also it lists the key utilities developed as part of this research and included in the program called *iSISMOD-utils*.

D.2 How To ...

D.2.1 Set up an iSISMOD model (major steps)

(i) In GMS, define location of 3D grid and discretization in horizontal and vertical direction (*Grid/Create Grid*)

(ii) Export 3D grid to 2D grid for future manipulation of 2D raster data (*Grid/Grid to 2D Grid*)

(iii) Define basic packages that will be used to make the groundwater component of the model, for example: Evapotranspiration, Recharge, River, Stream (*Modflow/Basic Package/Packages*) This operation will just initialize each of the packages for its future completion with actual data (see *How to complete data for each package*)

(iv) Populate each of the stress packages, with data depending on the type of stress.

(v) Define hydrogeological data for each groundwater layer: type of layer (confined/unconfined), hydraulic conductivity, storage coefficient and vertical conductivity (*Modflow/Block Center Flow Package*).

(vi) Define Stress period length, number of stress periods and number of time steps required within a single stress period (*Modflow/Basic Package/Stress Periods*)

(vii) Define type of boundaries. This implies the assignment of a specific code for each cell in the ibound array (*Modflow/Basic Package/Ibound*), as follows: -1 (fixed head), 0 (zero flow), +1 (variably head/flow).

(viii) Define starting heads (initial conditions). Enter 2D data for each layer (*Modflow/Basic Package/Starting Heads*)

(ix) Create basic Modflow superfile (*.mfs*) containing the instructions to read the different files by MODFLOW (*Modflow/Save simulation*).

(x) Edit superfile to suit iSISMOD. Edit .mfs file and delete all inverted commas in each line. Also, add a line containing the instruction: "ISIS **31** filename.str", to indicate that coupling with iSIS is required. It is recommended that the original .mfs file is preserved so that a Modflow interface can still be used to edit basic files and read results.

(xi) Edit Basic File (*.bas*) to include in the fourth line the instruction to read file 31, as follows
"11 0 0 0 19 0 0 20 0 0 0 10 12 0 0 0 0 0 0 21 0 0 0 0 **31**"

(xii) Create iSIS data file (*.dat*)

(xiii) Create iSISMOD control file (*.mfl*)

(xiv) Create iSISMOD plot file (*.plt*)

D.2.2 Populate Modflow packages

Populating the each of the basic files can be performed in any of the following ways:

(i) editing an existing file and importing it using the Modflow interface via the corresponding package menu.

(ii) filling the necessary values in each package menu. This is not normally recommended as it would have to be done manually for each stress period. GMS permits to speed up this process by specifying whether data from previous stress period is repeated.

(iii) using the map module of GMS. This feature permits to draw points, lines or polygons assigning to each of them the data required by any Modflow package. GMS permits to then "map to Modflow" each of the coverages filling automatically the data arrays of each package (*in Map Module, Feature Objects/Map to Modflow*). This is the recommended option.

D.2.3 Generate iSISMOD control file

Generating the control file involves three steps:

(i) the definition of which Modflow cells are associated to each iSIS node,

(ii) the specification of the ground level associated to each Modflow cell,

(iii) the completion of the file with the specification of the remaining parameters such as hydraulic conductivity and other keywords.

Points (i) and (ii) can be done by:

a. constructing polygons in any mapping software (ArcView, AutoCad or GMS itself) and naming them preferably with the associated iSIS node label.

b. assigning a value of –1 to each cell falling into each polygon, it means to each cell that will interact with iSIS. Export this information as a 2D data file.
c. export ground data (normally from the evapotranspiration surface used in the Modflow ET package) to a 2D data file.
d. Run iSISMOD-utils, option 19, to generate the Modflow cdh file with the head-time series associated to each cell. This utility required entering the following data:

    i. ibound file
    ii. Number of rows and columns
    iii. local 2D heads file containing ground data

The rest of the operations consist of data manipulation that can be performed in Excel.

D.2.4 Create MODFLOW Recharge and Evapotranspiration input files from external ASCII files

This operation was originated with the need to convert HYSIM files (.xys) into Modflow files. A typical .xys file has the following format:

XY1 1 396 0 0 0 0 "Infiltration__1963_to_1995_nw"		header line
1	0.0002238	i.e value of infiltration in m/day for stress period 1
2	0.0003193	...
3	0.0049082	...
4	0.0010669	...
5	0.0005223	...
6	0.001225	i.e value of infiltration in m/day for stress period 6

iSISMOD-utils, option 26, converts this file into a Modflow .rch (recharge) or .et (evapotranspiration) file:

(i) run iSISMOD-utils, option 26
(ii) enter .xys file

(iii) enter initial and final stress period

(iv) enter output time (daily or monthly)

(v) enter whether a recharge or an ET file is required

(vi) enter whether replication of data is required (this would be required if an average monthly value had to be used on a daily basis, in the absence of any better data)

D.2.5 Generate nested models

A nested model is a model (local) formed with data from another larger (regional) model. Once a local grid is constructed for the local model, then the following steps are required to pass data from the regional model (at a given resolution) to the local model (at a different, smaller resolution).

(i) Export the 2D data array set from the regional model from which data is to be passed to the local model (i.e. bottom elevation of a particular layer)

(ii) Convert the regional 2D data array to a scatter set of data points.

(iii) Read the local 2D grid file.

(iv) Interpolate from the regional 2D scatter set of data to the 2d local grid.

(v) Repeat steps 1 to 4 for each data array required.

D.2.6 Generate head-time boundary files

This is mainly required when a nested model is developed and boundary conditions (in the form of head-time) for the local model are required from a regional model. The steps to be followed are:

(ii) Use the ibound array to specify a value of –1 in each cell of the local model for which head time data from a regional model is required.

(iii) Export ibound array in ASCII format.

(iv) Read the 3D data set from the regional model from which data is to be extracted.

(v) Export regional 3D data to a regional 2D data array.

(vi) Convert the regional 2D data array to a scatter set of data points.

(vii) Read the local 2D grid file.

(viii) Interpolate from the regional 2D scatter set of data to the 2d local grid.

(ix) Save new local 2D data file.

(x) Run iSISMOD-utils, option 19, to generate the Modflow cdh file with the head-time series associated to each cell. This utility required entering the following data:

a. ibound file
b. Number of rows and columns
c. starting heads file
d. local 2D heads file
e. enter whether a daily or monthly boundary file is required.

D.2.7 Extract time series from a MODFLOW 2D results file

This process has to be carried out by running iSISMOD-utils, option 27:

(i) run iSISMOD-utils, option 27

(ii) enter file defining the cells for which results are required (this file has the same format as the iSISMOD plot file, *.plt*)

(iii) enter initial and final stress period for which results are to be extracted

(iv) enter output time as a multiple integer of the stress periods.

(v) enter number of rows and columns

(vi) enter type of output required (i.e. for single or multiple cells)

(vii) enter file with groundwater heads in 2D ASCII format

The result of this operation is a file for each plot defined in the *.plt* file with the following format:

format for a single cell output	format for a multiple cell output
time 1 value 1	time 1 cell 1 value 1 cell 2 value 2 cell 3 value 3
time 2 value 2	
time 3 value 3	
.... time n value n	time 2 cell 1 value 1 cell 2 value 2 cell 3 value 3

D.2.8 Generate flood probability maps (FPMs)

FPMs are generated running iSISMOD-utils, option 30.

(i) run iSISMOD-utils, option 30,

(ii) enter 2D data file containing the heads from layer 1 of an iSISMOD model,

(iii) enter start and end stress period of analysis,

(iv) enter coordinates that define the bounding rectangle for the FPM and the number of row and columns that define the grid of the model. This file is provided in the format used by IDRISI to document raster images.

```
file title :
data type  : real
file type  : ascii
columns    : 140
rows       : 140
ref. system : gkf5
ref. units : m
unit dist. : 1.0000000
min. X     : 5285000.0000000
max. X     : 5355000.0000000
min. Y     : 6015000.0000000
max. Y     : 6085000.0000000
```

(v) read file with ground data (2D data file) required to perform evaluation of the flood/no flood situation by comparing the surface water level with the ground level.

(vi) enter interval over which to count flood situations (i.e. when surface water level is above ground level). The interval must be a multiple of the stress period.

The utility then performs the following computations:

a. generates an IDRISI image for every stress period,
b. computes the number of flood situations over a period of time
c. calculates the flooding frequency for each raster element.

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