DEVELOPING ENVIRONMENTAL FLOWS FOR THE BALEH RIVER – HYDROLOGICAL AND GEOMORPHOLOGICAL PROCESSES IN THE BALEH CATCHMENT PRIOR TO DAMMING

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ABSTRACT

Dams have been built in many parts of the world since the earliest human civilizations, but currently there is a significant program of dam building underway in the tropics. Despite general awareness of the likely detrimental impacts of dams, the limited number of empirical tropical studies means that specific effects of dams on these important but imperilled ecosystems are hard to predict. Although the Functional Flows (FFs) concept is now prominent in the scientific and river management literature, it has been applied only to some very specific cases in tropical areas to guide dam operation (e.g. to support periodic flooding of floodplain areas). In these and many other cases, FFs have been applied retrospectively, to design operational flows for existing dams. The work presented in this thesis concerns development of flow recommendations prior to the construction of a large tropical hydropower dam on Baleh River, Sarawak. Specific objectives of the thesis are to: (i) develop a full statistical understanding of the natural hydrological regime of Baleh River, (ii) identify critical habitat forming discharges (those responsible for coarse sediment entrainment and transport) and relations between discharge magnitude and hydraulic habitat heterogeneity, (iii) to assess the impact of the dam and other land use changes on sediment connectivity, and (iv) provide specific recommendations for dam operation to support sediment entrainment and maintenance of habitat heterogeneity, and for management of lake levels to limit changes in connectivity.

The work involved analyses of historical data along with a number of empirical field data collection, modelling and remote sensing approaches. For Objective (i), a 51-year hydrological and hydro-climatological dataset was analysed in order to characterise the natural hydrological regime of the Baleh River. The analyses focussed on understanding the frequency, magnitude, duration, and timing of natural high and low flow events. For Objective (ii), HEC-RAS® models were built for 3 study reaches. These models were

used to simulate hydraulic conditions across the range of discharges extending from high to low flows. The output from the hydraulic models was combined with information on critical entrainment thresholds of sediment at the 3 reaches in order to understand which flows are capable of entraining sediment. The focus of these analyses was to understand whether the expected hydropower regime is likely to cause sediment entrainment in the way that occurs currently under the natural regime. The analyses also used HEC-RAS® to evaluate hydraulic habitat heterogeneity at low flow conditions. The HEC-RAS® modelling was integrated with Soil and Water Assessment Tool (SWAT® or ArcSWAT®) to understand flow magnitude in the river under different conditions of hydropower operation and rainfall (which would lead to tributaries downstream from the dam discharging high flows to the mainstem Baleh). In addition, the model coupled with the DEMs was used to look at the extent of exposure of gravel bars during low flow conditions. The SedInConnect model was used to understand patterns of sediment connectivity across the Baleh catchment. This model computes the sediment connectivity index (IC). For the modelling, it was necessary to develop DEMs and collate information on landcover in order to calculate topographic roughness and IC. Information on sediment entrainment was used to make recommendations about flows needed to maintain the geomorphic processes (i.e. bedload transport) post-impoundment that occur currently in the natural river. The low flow analyses were used to understand whether hydraulic conditions became more or less heterogeneous at low flows.

The hydrological analyses identified 5 distinct classes of high flow event in the Baleh (defined as 'Event Types'). These types have distinct magnitudes and durations. HEC-RAS® modelling indicated that the smallest of these events led to sediment entrainment of D_{16} and greater at the study sites, and that larger events resulted in increasing areas of the bed across the study reaches experiencing entrainment. The maximum likely hydropower releases are smaller in discharge magnitude than the smallest of these natural events. The modelling indicated that more or less no sediment entrainment would occur during normal hydropower operations. However, integration of the HEC-RAS® and ArcSWAT® models indicated that when the catchment is wet, tributaries are contributing enough flow to result in sediment entrainment at the study sites that equates to that under some of the higher natural event types. Hydraulic habitat heterogeneity was relatively high during low flows and dropped at moderate and high flows. Moreover, at low flows, gravel bars became exposed at some of the study sites adding to overall habitat heterogeneity. According to the IC models, the impact of historical landcover changes on connectivity between the Baleh and the Rajang has not been pronounced. However, the models predicted that future forest clearance and roads will have observable impacts on the connectivity between the Baleh and Rajang. The models indicated that the construction of the dam would result in a significant impact on connectivity, with the effects of impoundment being greater than those of road and landcover changes, leading to a large portion of the Baleh catchment being almost completely disconnected from the Rajang. The operation of the dam will affect IC upstream of the dam due to the changes in connectivity caused by different lake levels.

The HEC-RAS® modelling suggested that over time, in the absence of significant bed entrainment and transport of material, the bed could be expected to become progressively armoured and coarser, as seen in dammed rivers worldwide. However, the modelling also indicated that when the catchment is wet and downstream tributaries are contributing much additional water, flows in the Baleh will greatly exceed turbine releases and appreciable entrainment of bed material can be expected. Recommendations for geomorphic functional flows are made on the basis of these findings. Recommendations are to ensure that hydropower releases using the maximum number of turbines are made during times when the catchment is already wet, to ensure entrainment of bed sediment. Based on analyses of the natural regime, the recommendations include suggestions for timing and duration of such releases. They should last around 20 days, occurring 8 to 15 times per year, predominantly during the wet season. Low flow recommendations were made to occasionally allow dam releases to drop to 1 to 3 turbines to mimic natural low flow events. The recommendation for these events was to allow flow to drop to the natural respective monthly baseflows; these flows should last around 3 days with a frequency of at least 3 times per month during the wet season, and 2 times per month during the dry season. The dam will disconnect a major part of the Baleh catchment from the Rajang. The modelling suggested that the effects of the dam on connectivity will swamp the effects of landcover change and road construction on connectivity. Nevertheless, localised impacts of the road were predicted by the model, with an increase in connectivity on the upslope areas. It is recommended that measures to mitigate this are implemented as part of road construction and management. The model suggested that careful management of lake levels could be used to reduce the impact of the dam on connectivity in the upper part of the basin.

The study of functional flows presented in this thesis is of growing importance for sustainable catchment management, particularly in Southeast Asia, where rapid dam construction and vulnerability to the impacts of climate change are prevalent. It is one of few studies globally that has explicitly considered fluvial processes when developing functional flow recommendations. It is also novel in integrating reach scale HEC-RAS® models with catchment scale SWAT® models to help in the design of functional flow recommendations. As far as the author is aware, it is the only study globally to have used the SedInConnect model to understand the combined and interactive effects of damming, landcover change and road construction on structural connectivity at a catchment scale. These approaches can be applied to large rivers in Southeast Asia and other Global South regions, aiding sustainable catchment and water management. It is one of few functional flow studies to have been undertaken before dam closure, allowing us to implement functional recommendations in advance of construction, rather than retrofitting them to a river that has been regulated for some time. It is recommended that a program of monitoring is implemented in the Baleh in order to understand how the river changes in response to impoundment and the success of flow recommendations for maintaining sediment dynamics and habitat heterogeneity. This monitoring will provide the basis for adaptive management.

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PUBLICATIONS ARISING FROM THIS THESIS

Chapters 2 and 3 have already been published. The citation details are as follows:

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CHAPTER 1
General Introduction

1. GENERAL INTRODUCTION

1.1. BACKGROUND

Dams impede downstream conveyance of sediment, leading to sedimentary disequilibrium in river channels and accumulation of material in the impounding reservoirs (Kondolf, 1997; Vrhovnik et al., 2013; Chong et al., 2021a). Dams also alter flow and flood regimes, and so have direct impacts on river competence (Junk et al., 1989; Poff et al., 1997; Andersson et al., 2000; McCartney et al., 2007). Despite many new and proposed dams in tropical rivers, assessments of the impacts of these on fluvial dynamics have rarely been undertaken, especially in Southeast Asia (see details in Chapter 2).

Worldwide, freshwater biodiversity and ecosystem function have declined and deteriorated rapidly (Vörösmarty et al., 2010; He et al., 2019; Tickner et al., 2020). Damming rivers for human water security and water extraction for societal uses alters freshwater ecosystem structure and function (Mirchi et al., 2014). Consequently, there is increasing pressure to find sustainable approaches to balance the complex trade-offs between human and environmental water needs. The most widely used approach to sustain both human water security and freshwater ecosystems is to establish environmental flows (e-flows) - defined as "the quantity, timing, and quality of freshwater flows and levels necessary to sustain aquatic ecosystems which, in turn, support human cultures, economies, sustainable livelihoods, and well-being" (Arthington et al., 2018).

Many countries recognise that e-flows should be implemented and/or incorporated into water management and policy to ensure water sustainability for both humans and ecosystems. The Brisbane Declaration (2007) and the Global Action Agenda on

Environmental Flows (2018), which set a common direction and synthesis for international e-flows implementation, were endorsed by 57 countries (Brisbane Declaration, 2007; Arthington et al., 2018). Additionally, member states of the United Nations have agreed to work towards simultaneously meeting two freshwater-related Sustainable Development Goal targets (SDG's) by 2030: “Increase water-use efficiency across all sectors and ensure sustainable withdrawals and supply of freshwater...” (Section 6.4), and “protect and restore freshwater ecosystems...” (Section 6.6; UN, 2018).

Hydrologic modification through damming has been shown to homogenise flow regimes and change flow seasonality, altering the magnitude, frequency, and variability of discharge, which can decrease peak flows and flood pulses and increase baseflows (Poff et al., 2007). As a result, e-flows implementation often seeks to either restore flow regimes to a pre-dam flow regime (Bednarek & Hart, 2005), establish dynamic, characterisation-based flows based on river types and flow–ecology relationships (Poff & Zimmerman, 2010), or design flows to maximise ecological outcomes (Acreman et al., 2014; Chen and Olden, 2017; Poff et al., 2017). These approaches can improve freshwater ecosystem function and biodiversity by addressing the life cycle needs of aquatic and riparian species (Carlisle et al., 2010; Merritt et al., 2010; Mims and Olden, 2012; Olden et al., 2014), maintaining the natural structure of aquatic communities (Bogan and Lytle, 2011; Tonkin et al., 2017), improving water quality (Nilsson and Renöfält, 2008), restoring sediment regimes (Topping et al., 2010), and sustaining ecosystem goods and services (Gopal, 2016). Thus, e-flows can both support freshwater ecosystem conservation and provide socio-economic benefits to human societies.

Species evolve and adapt to the conditions set by the natural flow regime of the river, including temporal patterns of variation. Thus, to establish an appropriate environmental flow regime, it is necessary to first characterise hydrological variability

(Zhang et al., 2012; Poff et al., 2017; Yang et al., 2021). The range of intra and interannual flow variation, along with magnitude, seasonality, duration, frequency, and rate of change are key aspects of variability recognised as important for preserving natural biodiversity and the integrity of aquatic ecosystems (Poff et al., 1997; Puig et al., 2016). Therefore, in regulated rivers it is necessary to establish environmental flow regimes capable of reproducing natural patterns of flow variability (Paredes-Arquiola et al., 2014; Ahn et al., 2018).

1.2. River Hydromorphology and Ecosystem Functioning

Hydromorphology (or hydrogeomorphology) is the science which studies the complex interactions between the flow of water and channel form, and is key to understanding river physical condition, water quality, biodiversity, and river ecosystem functioning. Channel form and water flow are key components of river condition, and so good hydromorphic status can be considered as being the integrity or 'naturalness' of hydrologic and geomorphic processes.

Natural processes related to sediment erosion, transport and deposition play a major role in shaping channel form. In order to support these channel processes, sediment needs to be supplied into the river network. Sediment connectivity is the connected transfer of sediment from a source to a sink in a system via sediment detachment and transport, controlled by how the sediment moves between all geomorphic zones in a landscape. Connectivity between the wider catchment and the river channel varies in space and time (Brierley et al., 2006; Bracken et al., 2015), as a function of: (i) the morphological complexity of the catchment, such as its relief, stream network density, catchment shape, soil type and surface roughness (e.g. Borselli et al., 2008; Baartman et al., 2013; Cavalli et al., 2013), (ii) the spatial organisation of vegetation (Cammeraat, 2002; Foerster et al., 2014), and (iii) anthropogenic modifications of the landscape (land use and drainage system changes, road network configuration) (Tarolli and Sofia, 2016). Much work has now shown the importance of connectivity for the integrity of physical and ecological processes in catchments (Wheaton et al., 2011). Anthropogenic changes in catchments that alter connectivity can therefore impact river integrity. River management should pay much more attention to issues related to connectivity (Fuller et al., 2018).

Hydromorphological impacts are diverse and can affect stream channels, riparian areas and floodplains either directly (e.g. extraction of gravel, protecting the banks with riprap and building levees), or indirectly (e.g. impervious surfaces in the drainage basin increase flashiness). Their effects on channel form and biological communities have been extensively reviewed (e.g. Brandt, 2000; Kingsford, 2000; Corenblit et al., 2007). Landcover change and associated soil erosion have increased sediment delivery to rivers because of how they increase connectivity. However, dams reduce connectivity by trapping sediment, e.g. a 20% decrease in the amount of sediments reaching the oceans worldwide has been attributed to dams (Syvitski et al., 2005). Sediment starvation below dams affects channel form and dynamics (Shields et al., 2003; Graf, 2006; Dade et al., 2011), and has important consequences for ecosystem functioning. For instance, reservoirs in the Ebro River (Northern Spain) retain 100% of bedload and 99% of suspended load (Tena et al., 2011), and the historically turbid lower reaches of the river are now dominated by submerged macrophytes (Sabater et al., 2008a); these macrophytes have important effects on retention of sediments and dissolved phosphorus (Julian et al., 2011).

Compared to Europe, North America and Australia, water management in Malaysia is poorly developed and as yet there is no nation-wide implementation of Integrated River Basin Management (IRBM). Also, there are currently no nationally applied policies or legislation requiring the use of e-flows to support flow management in dammed rivers.

E-flows need to target understanding the importance of both low and high flows (Petts 1996). For example, Hill and colleagues (1991) described the ecological importance of low flows, bank full flows, overbank flows, and extreme valley-inundating floods. Petts (1996), Richter and colleagues (1996), and Poff and colleagues (1997) later introduced ecological and geomorphological relationships to other attributes of the flow regime, including the timing, duration, frequency, and rate of change of flows. These works helped crystalised the notion of functional flow as being components of the hydrograph that serve specific geomorphic, biogeochemical or ecological functions (sensu Escobar-Arias and Pasternack, 2010; Ward et al. 2002; Vidon et al. 2010).

1.3. THE BALEH HYDROELECTRIC PROJECT

The Baleh Hydroelectric Project (HEP) is a key state infrastructure and hydro-industrialisation development project, set to meet the rising energy demands from energy-intensive industries within the Sarawak Corridor of Renewable Energy (SCORE). It helps support Sarawak's ambition of achieving a high-income and developed status by 2030 (Sarawak Energy Berhad, 2019).

The Baleh HEP project is Sarawak Energy's largest hydropower project to date and is targeted for completion in 2027. It will generate 1,285 MW of energy. The 188 m-high concrete-face rockfill dam (1° 48' 9.00" N, 113° 46' 22.00" E) is located 95 km upstream from its confluence with the Rajang River, in the Kapit administrative division. Batang Baleh is a large river ("Batang" translates to "large"), averaging approximately 200 m wide and with a mean annual discharge (Telok Buing gauging station) of 1016 m^3/s. Average rainfall in the catchment is 3868 mm, exceeding 5000 mm in many years. Further details of the catchment and its flow regime are given in Chapter Three.

1.4. Research Aims and Objectives

This research stems from the requirements of the International Hydropower Association's sustainability protocols which govern the operation of dams. The association has a Hydropower Sustainability Assessment Protocol which is adhered to by Sarawak Energy Berhad (Sarawak Energy Berhad, 2019). As part of this protocol, the dam operators are required to undertake environmental impact assessments and operate the dam in a sensitive way to minimise impacts on river ecosystems and local communities. This research was undertaken to provide data to support such operation of the dam.

The aim of the work presented in this thesis is to provide functional flow recommendations for Baleh dam based on an understanding of catchment and channel dynamics. Specific objectives are to: (i) develop a full statistical understanding of the natural hydrological regime of Baleh River, (ii) identify critical habitat forming discharges (those responsible for coarse sediment entrainment and transport) and relations between discharge magnitude and hydraulic habitat heterogeneity, (iii) to assess the impact of the dam and other land use changes on sediment connectivity, and (iv) provide specific recommendations for dam operation to support sediment entrainment and maintenance of habitat heterogeneity, and for management of lake levels to limit changes in connectivity.

1.5. Dissertation Structure

This dissertation is structured into six chapters. The remainder of this current chapter provides an overview of the methods and approaches used to address each of the research objectives. Chapters Two, Three, Four and Five are the outcomes from the research, presented in a scientific publication format. Chapter Two consists of a systematic review of what is known about the impacts of impoundment on fluvial dynamics in tropical rivers. This chapter has already published as a paper (Chong et al., 2021a). This paper was written and published early on in the thesis period and focusses on impoundment and fluvial processes. To make Chapter Two a more appropriate overall review of literature relevant to this thesis, additional sections have been added that were not in the published paper. These additional sections include material on sediment connectivity.

Chapter Three provides a detailed hydrological analysis of the Baleh River in order to provide an understanding of the natural flow regime of the river. This chapter has also been published as a paper (Chong et al., 2021b). Chapter Four analyses connectivity across the basin and how connectivity is likely to be affected by damming and associated land use and landcover changes. Chapter Five assesses the role of high flows in initiating sediment entrainment and how such entrainment may be affected by the dam. It also looks at hydraulic conditions at natural low flows and how these conditions may be impacted by the dam. Both these assessments are used to provide recommendations for functional flows. Chapters Four and Five are written as standalone pieces, and so have their own introductions, methods, results, and discussion sections. The final chapter of this thesis (Chapter Six) consists of a synthesis and suggestions for future research. References and appendices are included at the end of each chapter. Figure 1.1 provides an overview of the thesis structure and methods/tools adopted.

The thesis represents output from a larger project designed to provide flow recommendations to support a range of functions. For the sake of completeness, the various elements covered by this larger project are shown in Figure 1.2. The elements represented in blue boxes are those covered by this thesis; those in green are aspects of work covered by other research.

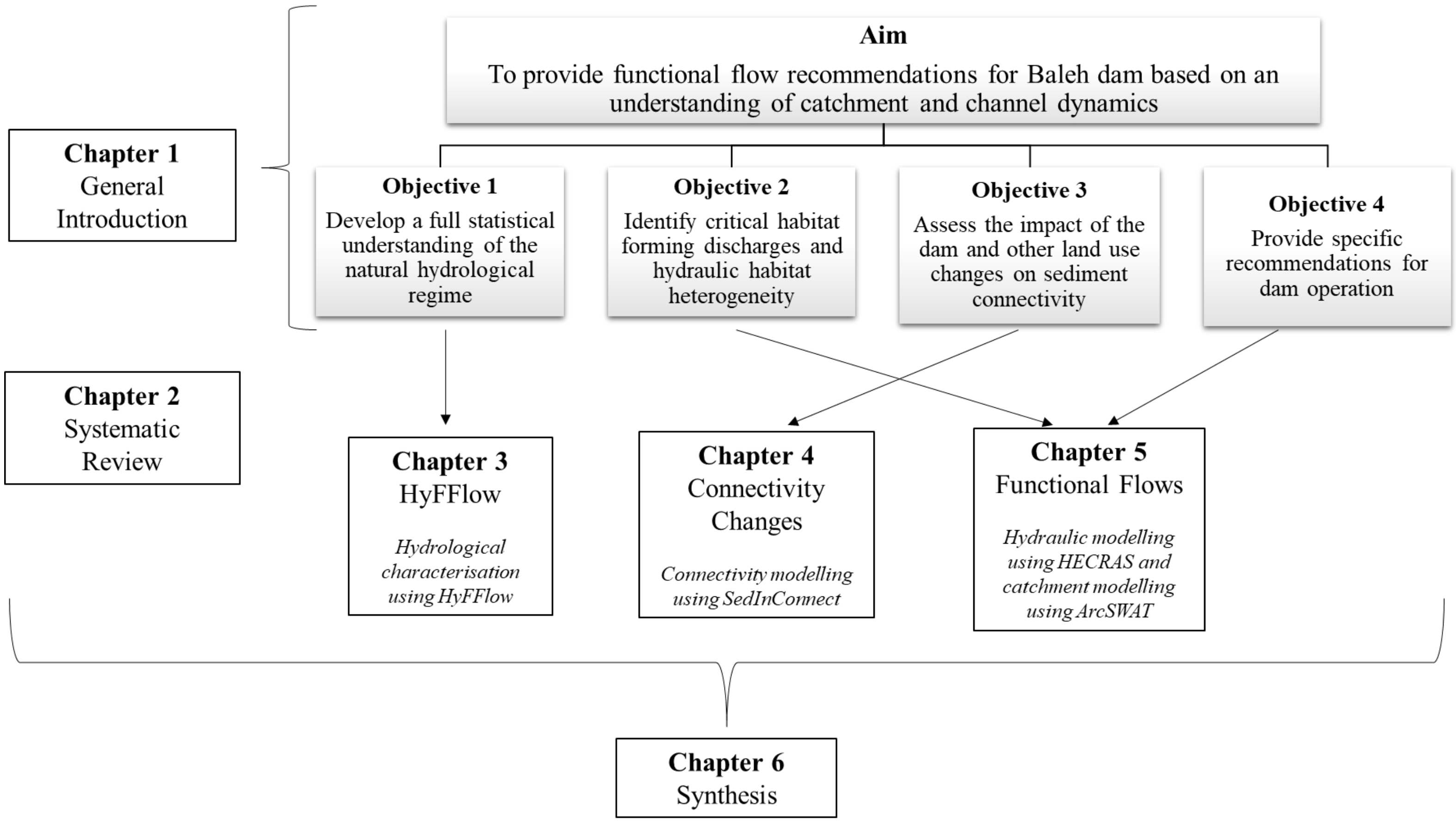

Figure 1.1 An overview of the thesis structure and methods/tools adopted.

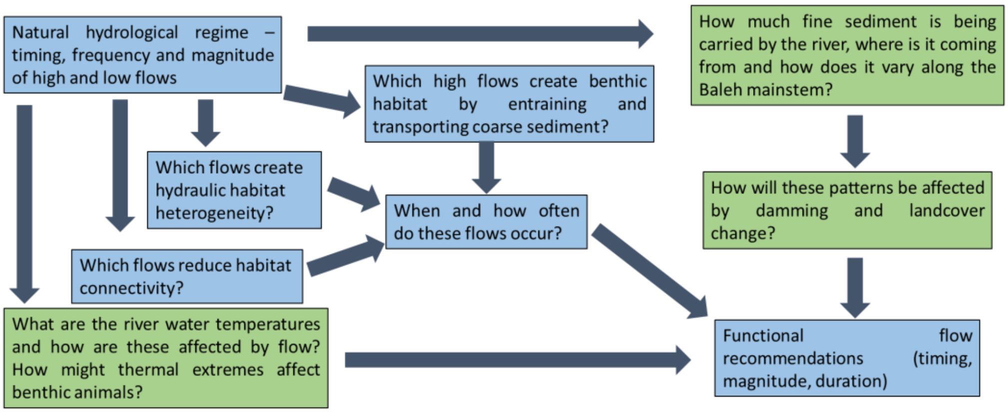

Figure 1.2 A conceptual diagram of the project workflow to illustrate how information from each element will be used to help provide functional flows recommendations.

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CHAPTER 2
Systematic Review

2. SYSTEMATIC REVIEW

ABSTRACT

A major programme of dam building is underway in many of the world's tropical countries. This raises the question of whether existing research is sufficient to fully understand the impacts of dams on tropical river systems. This chapter provides a systematic review of what is known about the impacts of dams on river flows, sediment dynamics and geomorphic processes in tropical rivers. It considers the issue of connectivity, both in terms of longitudinal connectivity and the connectivity between stream networks and their catchments. The systematic part of the review was conducted using the SCOPUS® and Web of Science® databases, with papers analysed to look for temporal and geographic patterns in published work, assess the approaches used to help understand dam impacts, and assess the nature and magnitude of impacts on the flow regimes and geomorphology ('hydromorphology') of tropical rivers. As part of the review, a meta-analysis was used to compare key impacts across different climate regions. Although research on tropical rivers remains scarce, existing work is sufficient to allow us to draw some very broad, general conclusions about the nature of hydromorphic change: tropical dams have resulted in reductions in flow variability, lower flood peaks, reductions in sediment supply and loads, and complex geomorphic adjustments that include both channel incision and aggradation at different times and downstream distances. At this general level, impacts are consistent with those observed in other climate regions. However, studies are too few and variable in their focus to determine whether some of the more specific aspects of change observed in tropical rivers (e.g. time to reach a new, adjusted state, downstream recovery distance) differ consistently from those in other regions. The review helps stress the need for research that incorporates before-after comparisons of flow and geomorphic conditions, and for the wider application of tools available now for assessing hydromorphic change. Very

few studies have considered hydromorphic processes when designing flow operational policies for tropical dams. Moreover, studies of sediment connectivity in dammed rivers tend to focus on longitudinal connectivity. Future research should also look into the importance of lateral connectivity in hydrological, geomorphic and ecological terms.

2.1. INTRODUCTION

2.1.1. CONTEXT, AIMS AND OBJECTIVES

A global dam construction boom has been transforming the world's low-latitude river systems (Zarfl et al., 2015; IEA, 2016), with new mega-reservoirs (i.e. volume >10 km^3) coming onstream at a rate of one per year in tropical regions over the period 2001-2011 (Figure 2.1; Winton et al., 2019). Twelve dams in Southern and Eastern Asia have a capacity over 5 km^3 (i.e. = 5×10^9 m^3) (5 in Thailand, 2 in Malaysia, 2 in Pakistan, 1 in Bangladesh, 1 in Lao People's Democratic Republic and 1 in Vietnam), with these accounting for 17% of the total dam capacity in the region (Table 2.1; Frenken, 2012). The countries in Southeast Asia (SEA) have announced plans to construct a combined total of 78 gigawatts (GW) of new hydroelectric generating capacity; once these projects are completed, total capacity will triple the 39 GW capacity of 2012 (Figure 2.2). China has already constructed 6 major dams (i.e. dam height > 15 m) along the upper portion of the Mekong River, and an additional 71 Mekong hydroelectric dams in other countries in SEA are planned for completion by 2030 (IEA, 2016).

Many of the world's largest rivers are located in tropical countries (Latrubesse et al., 2005; Sinha et al., 2012), where increasing electricity demand makes hydropower an attractive (IEA, 2019), 'clean energy' source as well as a valuable source of revenue. Much of the expansion of hydropower dams globally (70%) is happening in tropical SEA (Zarfl et al., 2015). In terms of exploitation of river systems, tropical regions and SEA in particular are therefore drawing the world's gaze.

The report of the World Commission on Dams (WCD, 2000) asserts that the completion of any dam project should contribute to the sustainable advancement of human welfare. This requires projects to be conceived, constructed, and operated in ways that are socially equitable, economically viable and environmentally sustainable (WCD, 2000). However, a wide set of undesirable effects of dams have been reported, including community displacement, declines in fisheries, impacts on floodplain agriculture and safety hazards associated with fluctuating flows. Trade-offs between these effects and dam benefits (hydropower production, flood control, irrigation, domestic water supply, navigation) are rather hard to quantify (ICEM, 2010) and many dam schemes have become highly controversial (Kornijów, 2009).

There are a number of specific effects of dams on downstream river channels and ecosystems. The nature and magnitude of these effects link to the relative size and operation of the dam. For example, effects are determined by the relative capacity of the reservoir, which can be expressed using the Impoundment Ratio (IR; Batalla et al., 2004), and particularly by whether the dam has a hydropeaking regime, or the relatively constant pattern of water release associated with water supply reservoirs (Batalla et al., 2021). One overarching concern is that of spatial fragmentation (Anderson et al., 2008; Farah-Pérez et al., 2020), with an estimated 59% of the world's largest 227 rivers now fragmented as a result of river sections up and downstream from dams becoming disconnected (Nilsson et al., 2005). Hydrological change and fragmentation, especially related to loss of longitudinal sediment connectivity, lead to major changes in downstream river channels that have implications for ecosystem structure and function.

Ecological communities are highly variable and dynamic, with structure and function intimately linked with a highly changeable habitat that includes effects of both high and/or low flow, or in certain seasons depending on their geographic location (Vander Vorste et al., 2016). These organisms have, in general, developed a variety of morphological, behavioural, and life history characteristics to survive during those high shear stress flows or hot, low oxygen low flows (Lake, 2011; Lancaster & Downes, 2013). The refugia for escape also depends upon spatially heterogeneous rivers. The use of this escape route is likely to depend on the geomorphic structure, substrate size, and permeability of sediments in a river or stream network, with these characteristics reflecting the strength of hydrologic connectivity, modulated by sediment connectivity (Fuller and Death, 2018). Sediment transfer takes place on hillslopes, between hillslopes and channels (slope–channel coupling), between floodplain and channel (bank erosion, floodplain deposition: lateral and vertical accretion), and within channels (longitudinal connectivity associated with sediment transport) (Fuller and Death, 2018). Growing recognition of the importance of connectivity had ensured it has received ever-increasing attention in the literature.

This chapter provides a review of what is known about the impacts of dams on flows and geomorphic processes and conditions ('hydromorphology') in tropical rivers. The specific objectives of the review are to: (i) quantitatively assess how much published work on the hydromorphic impacts of dams on tropical rivers exists, (ii) characterise the nature of published work, in terms of its exact focus (e.g. impacts on hydraulics, flow regimes, sediment transport), scale and approaches, (iii) synthesise findings to assess whether there are consistent patterns in tropical river responses to impoundment, and (iv) identify critical knowledge gaps, to help set a research agenda to improve understanding of dam impacts on tropical rivers. The chapter starts by stressing why it is important that studies are conducted in tropical regions. This is followed by the main findings of the review, organised according to the four objectives.

The chapter is based almost wholly on a published paper (Chong et al., 2021). However, to ensure that the chapter provides a more complete review of literature relevant to the thesis, additional sections dealing with lateral connectivity have been added. This means that the chapter is essentially a systematic review of impoundment impacts, with the additional of other material covering connectivity but which was not collected or analysed using a formal systematic approach.

2.1.2. The Need For Tropical River Studies

All rivers convey water and sediment downstream and are governed by the same physical laws and processes related to fluid dynamics and sediment transport. All dams trap sediment and so they alter supply to the downstream river, and all store and release water in ways that alter the hydrological regime, as well as the connectivity, continuity, and competence of the river. We can therefore expect that, in very broad terms, hydrological and geomorphic impacts of dams located in tropical regions should parallel those in other climate regions. However, there are several reasons why we might expect some of more detailed, specific aspects of tropical river responses to damming to differ from those in other regions.

Tropical rivers have characteristic hydrological regimes that differ from those in other climate regions (Table 2.2). For example, many tropical rivers are strongly monsoon-driven, and this dictates patterns of discharge variation and magnitude (i.e. flow/flood regimes) over the course of the year. Monsoonal regimes differ markedly from those in both temperate and Mediterranean regions where, in the case of the latter for example, rivers may have very little or no flow during the dry summer months (Garcia et al., 2017). Such differences between regions reflect differences in rainfall, but also the much higher runoff coefficients of tropical rivers (Table 2.2 and references therein). The extent to which the post-dam hydrological regime differs from the natural one is a key factor affecting downstream river dynamics. As natural flow regimes differ between climate regions, the relative change associated with a given type of dam operation (e.g. hydropower, water diversions for irrigation) is therefore likely to differ. The exact nature of this change is important from an ecological perspective because many species have life cycles that are strongly coupled to the flow regimes of the rivers they occur within; e.g. fish life cycles have evolved so that spawning occurs at times of the year when flows are suitable (Moir et al., 2004), while insects have life cycle phenologies such that egg deposition (Peckarsky, 1980) and larva to adult emergence (Lytle, 2002) occurs during periods of optimum flow conditions. Turgeon et al. (2019) have already suggested that tropical fish assemblages are more sensitive to impoundment than those in other regions. It is therefore important that studies are undertaken to assess the nature and degree of flow alteration in tropical rivers following impoundment and determine whether these changes differ in any consistent way from those in other regions. Our synthesis of published studies addresses this point.

The second reason that dam impact studies are needed in tropical regions relates to sediment loads and dynamics. Cold, high-latitude rivers generally have lower sediment loads than tropical ones (e.g. data in Holeman 1968; Milliman and Meade, 1983; Milliman and Syvitski, 1992; Syvitski et al., 2000, Syivitski and Milliman, 2007). Rivers in temperate Europe have very low sediment yields (i.e. <10 t $km^{-2}yr^{-1}$; Milliman and Farnsworth, 2013), while Mediterranean systems have higher but highly variable sediment yields, generally 0.9-3000 t km^{-2} yr^{-1} for catchments with areas between 10 and 100 km^2 (Vanmaercke et al., 2012; Tuset et al., 2016). Tropical rivers have relatively high and constant sediment yields (Figure 2.3a; Syvitski et al., 2014). For example, they typically have a more constant and high suspended sediment concentration (SSC), unlike most temperate and Mediterranean systems where most of the annual suspended load is conveyed during floods (Figure 2.3b), with SSCs lower for most of the time. Such differences mean that a dam that traps most of a river's fine sediment load and releases water with a relatively constant and low amount of suspended material will have different relative effects on temporal patterns of SSC in tropical versus temperate and Mediterranean systems. Syvitski et al. (2014) stressed that due to warm and low-viscosity water, there may be reduced competence for bedload transport in tropical systems.

A third reason why it is important that studies of dam impacts are conducted in tropical rivers is because the nature and pace of post-impoundment adjustment may differ from other regions. Petts and Gurnell (2005) developed a conceptual model to represent the trajectory of geomorphic change in downstream river channels following dam closure. The model described changes from the natural to an adjusted regime state, between which several transient states occur. The time between natural and adjusted states was termed 'relaxation time'. Petts and Gurnell (2005) stressed that relaxation time depends critically on the magnitude of changes to discharge and sediment supply but can be modified by inputs from tributaries downstream from the dam. Figure 4 in their paper presented hypothetical models of relaxation for different geographic regions, as a function of differences in flow and sediment supply. It is timely – now more than 15 years after publication of this paper – to review the extent to which published work now allows us to relate the geomorphic responses and relaxation times observed in tropical systems to the models proposed by Petts and Gurnell (2005) and, where possible, compare these to other systems. This is addressed as part of the synthesis.

There is much to be learnt from the many studies of dam impacts undertaken in higher-latitude rivers (e.g. Wilcock et al., 1996; Batalla et al., 2004; Vericat and Batalla, 2006a; Singer, 2007; Lobera et al., 2017; Piqué et al., 2017). Nevertheless, the three points articulated above indicate that it is also important that studies are conducted to assess changes in tropical rivers, because of potential differences in more detailed aspects of their response.

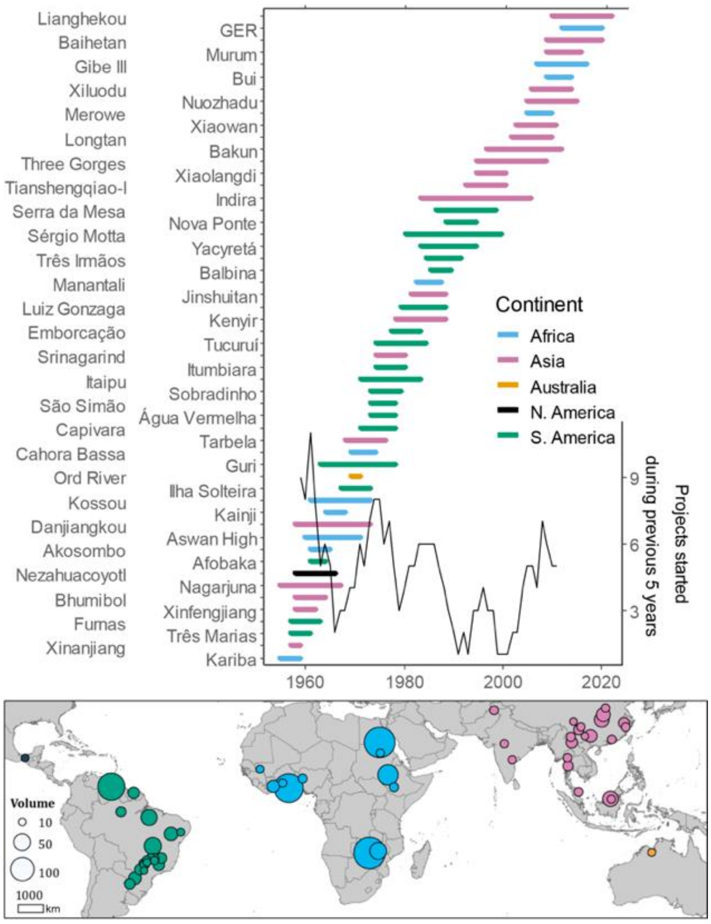

Figure 2.1 Construction history of the world's 54 largest reservoirs located below ±35◦ latitude. Grand Ethiopian Renaissance abbreviated as GER. Volume in map legend is in cubic kilometers (Winton et al., 2019).

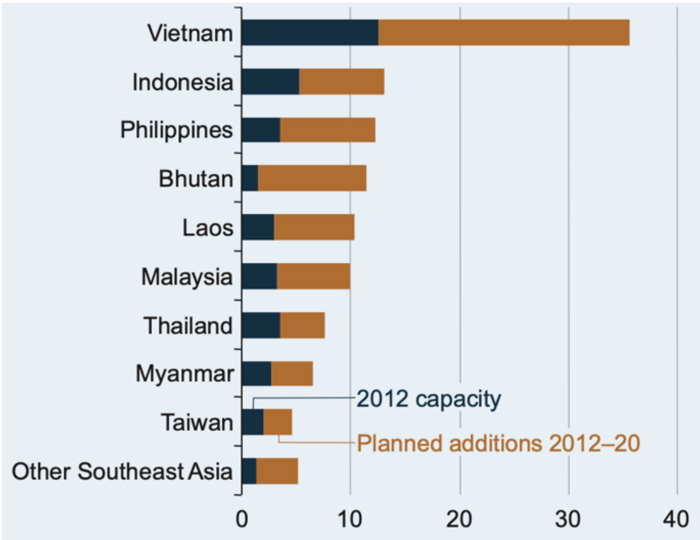

Figure 2.2 Hydroelectric generating capacity in Southeast Asia, 2012 and planned additions from 2012 to 2020, by country (GW) (IEA, 2016).

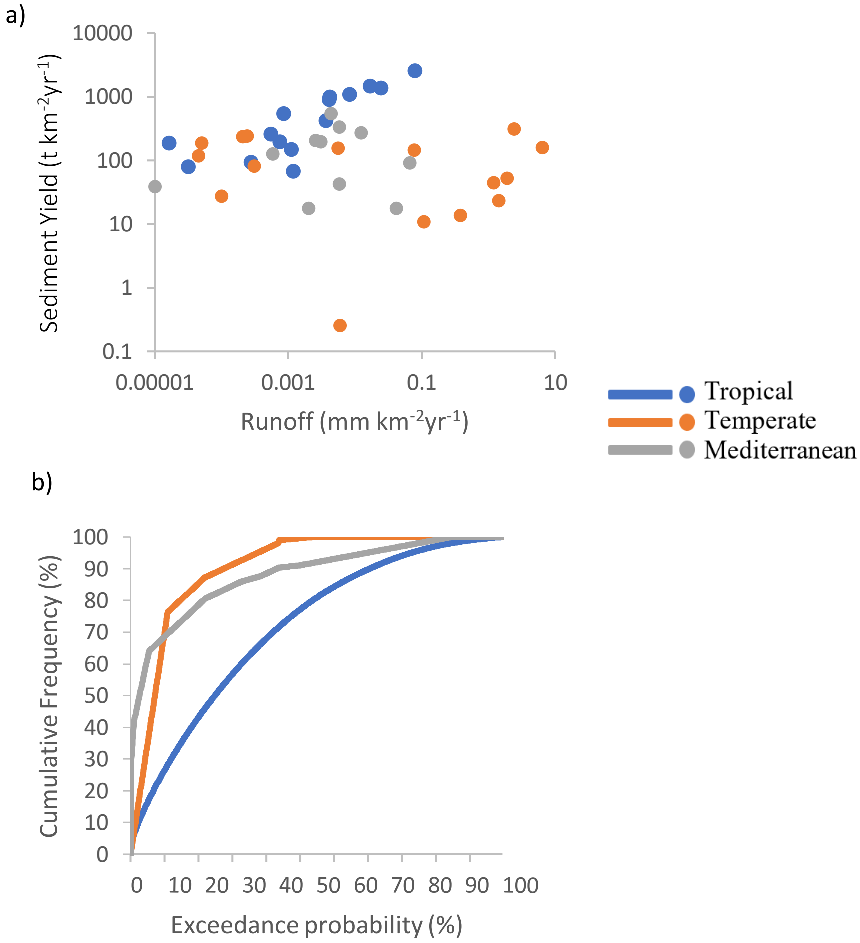

Figure 2.3 Relations between runoff, and sediment yield (a) and examples of suspended load frequency curves; (b) for rivers in different hydroclimatic regions. For (a), data points are from Holeman (1968), Milliman and Syvitski (1992) and (b) data are from Lum (unpublished MRes thesis), Roy and Sinha (2014) and Vericat and Batalla (2010).

Table 2.1 Subregional breakdown of dam capacity in Southeast Asia (Frenken, 2012).

Subregion	**Dam Capacity**	
	km^3	**% of the region**
East Asia	589.1	56
South Asia	277.4	26
Mainland Southeast Asia	128.1	12
Maritime Southeast Asia	53.2	5
Total Region	**1047.7**	**100**

Table 2.2 Summary of the main characteristics of hydrological regimes in tropical and temperate rivers (based on data in Nosita, 1983; Perera and Wijesekera, 2011; Wohl et al., 2012; Syvitski et al., 2014).

Main characteristics of flow regime			
Characteristics		**Tropical rivers**	**Temperate rivers**
Seasonality		Occurs on monthly scale, where dry and wet periods are influenced by equatorial convective rainfall and monsoon rainfall	Influenced by clear differences between winter and summer precipitation and temperatures. In some areas, there is a major influence of snow and ice ablation.
Flow ranges (specific discharges)	**Low flow ($m^3s^{-1}km^{-2}$)**	0.001-0.01	0.001-0.005
	High flow ($m^3s^{-1}km^{-2}$)	0.011-0.03	0.006-0.015
	Flood ($m^3s^{-1}km^{-2}$)	> 0.03	>0.015
Runoff coefficient		0.05-0.87	0.02-0.155

2.2. METHODS

Systematic bibliometric analyses have been used successfully to obtain and integrate information from large numbers of scientific papers and to identify trends and patterns in published literature (Liu et al., 2011; Tao et al., 2015; Liu et al., 2016). This approach, using both SCOPUS® and Web of Science®, is used here to help understand and articulate key aspects of the published literature on tropical dams, and in turn to identify knowledge gaps.

Due to its comprehensiveness and high-quality records (Burnham, 2006; Bosman et al., 2006), the SCOPUS® database was first used to conduct a search. A preliminary SCOPUS® search was conducted to collect any article within the SCOPUS® database related to the study topic. The objective of this initial search was to create the framework for subsequent filtering that would produce the set of articles on which the qualitative and quantitative analyses could be performed. The preliminary search was developed using the Boolean operators ‘AND’ and ‘OR’ combined with specific search terms such as “Southeast Asia”, “tropics” etc. A combined field code that searched for the key terms in abstracts, keywords, and article titles (TITLE-ABS-KEY) was applied. The search string started with the geographical locations and included keywords together with the 11 countries in the SEA region. Other tropical countries were also included, with these defined using WWF Freshwater Ecoregions of the World (FEOW) (Abell et al., 2008). The search string also included terms related to the subject area, such as “dam impacts”, “downstream effects”, “hydrology”, and “geomorphology” (Appendix A). This preliminary search resulted in identification of 78 published studies.

A four-step filtering process was then conducted: (1) ‘search within the search’, as SCOPUS® permits a further detailed identification of articles within an initial search; (2) exclude keywords not related to the search (unrelated indexed keywords, e.g. names of non-tropical countries); (3) include only articles in English language and final publication stage; (4) limitation of the research disciplines involved in the study to the following areas classified in SCOPUS®: Earth and Planetary Sciences, Environmental Science, Agricultural and Biological Sciences, and Energy. This filtering yielded 39 articles.

To ensure that the SCOPUS® search did not overlook any significant published studies, an additional search was conducted using Web of Science®. This additional search involved applying the keywords “largest dam in *X*” (where *X* represents the country name) for all the tropical countries listed in Appendix A. Web of Science® was then used to look for any publications related to these largest dams. This search yielded an additional 15 published studies.

The literature cited in these 54 articles (39 from SCOPUS® and 15 from Web of Science®) was then followed up, to check for any published work not detected in the systematic searches. Many of the cited papers concerned wider impacts of dams (e.g. ecology, biogeochemistry) with hydrology or geomorphology only treated peripherally, so were not included in the review. Others were excluded because they could not be accessed.

The initial search, filtering and then follow-up searches, yielded a final total of 82 papers that were systematically reviewed. Papers were classified into categories, depending what they mainly focused on (flow regime, hydraulics, sediment transport or geomorphology). Relative frequency of these foci was assessed, along with the frequency of studies with multiple foci. Papers were also classified according to whether they used both pre- and post-dam data. The focal categories formed the basis of the scientific part of review, in which evidence of impacts of tropical dams on flow regime, hydraulics, sediment transport or geomorphology was determined. The approaches used in each paper and the scale(s) at which work was conducted were assessed. To help structure assessment of the approaches and specific methods used in the papers, the classification devised by Kondolf and Piegay (2002) was applied. This classification was developed from a quantitative analysis of tools used in 496 published papers. Finally, whether or not each paper addressed river management issues (e.g. suggestions or designs for environmental or functional flows) was also established. As our search terms did not include phrases related to environmental or functional flows, the treatment of river management is not meant to be systematic; instead, it is used simply to indicate the extent to which papers dealing with flow or geomorphic change used this to help inform management.

2.3. Review Findings

2.3.1. Publication Patterns and Foci

Temporal patterns in publication of the 82 papers are shown in Figure 2.4. Based on the search string, the first empirical paper dealing with dam impacts on tropical river hydromorphology can be considered as being that of Pickup (1980). There was an increase in publication rate between 2006 and 2016, but evidence of a more recent decline.

Papers dealing with impacts on flow regime were most numerous (63 studies, 57%), followed by those focussed on sediment transport (27 studies, 24%); very few dealt with either flow hydraulics or geomorphology (Figure 2.5). A number of the papers dealt with more than one of these focus areas The combination of flow regime and sediment transport was most frequent (30%, 13 studies), followed by 2 combinations that looked at flow regime and hydraulics (16%, 7 studies), flow regime and geomorphology (9%, 4 studies). Very few looked at all four areas (7%, 3 studies) or a combination of flow regime, sediment transport and geomorphology (7%, 3 studies). Eleven papers (13%) provided guidance for management. Five of the papers (9%) included estuaries and deltas in their analyses; for the sake of completeness, these were included in the review.

Most studies were undertaken in either Brazil or the Mekong River Basin (Figure 2.6; Table 2.3 gives further details). The two parts of Mekong are often treated separately - the Lower Mekong Basin (LMB) and Upper Mekong Basin (UMB, sometimes referred to as the Lancang Basin). LMB extends from China (21% of the basin area) across Laos (25%), Thailand (23%), Cambodia (20%), Vietnam (8%), and Myanmar (3%), with the upstream portion of the basin lying in China. According to the recent dam status updates in the Greater Mekong Dam Database (WLE-Mekong, 2017), 64 of the 187 existing and proposed hydropower dams in the Mekong basin had been commissioned by June 2017

(Hecht et al., 2019). Damming of the Amazon has ensured that, along with the Mekong, this basin has been a major focus of published studies. In Brazil, the National Plan for Electric Energy 1987/2010 set out a strategy for over 30 dams to be built on Amazonian rivers, to achieve a total generation capacity of 64,572 MW of electric energy over a 25-year period (Cummings, 1995).

Despite the magnitude of dam construction, there are scarcely any studies in SEA apart from the Mekong River. There are, for example, very few studies from the impounded Indian rivers such as the Godavari, Mahanadi, and Krishna, Burmese rivers such as the Irrawaddy and Salween, or Thai rivers such as Chao Phraya. Malaysian rivers such as the Rajang, with large recent and planned impoundments, lacked comprehensive peer-reviewed scientific study. There are few studies from west and central Africa, with exceptions being published work on the Manantali and Felou Dams in the Senegal River basin, and Kafue Dam in Zambia (e.g. Mumba and Thompson, 2005; Zurbrügg et al., 2012; Sakho et al., 2017).

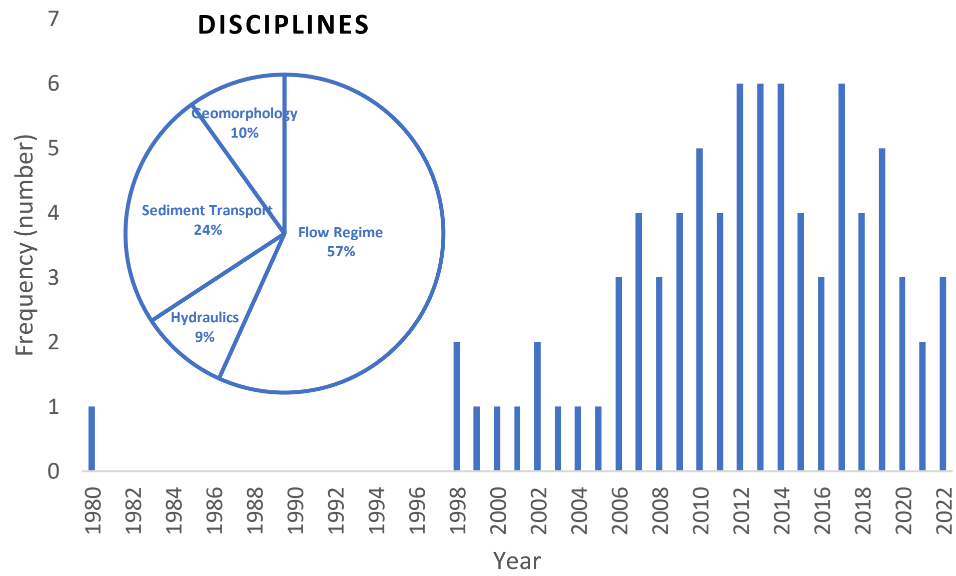

Figure 2.4 Publication dates and main subject foci of the 82 publications included in this review.

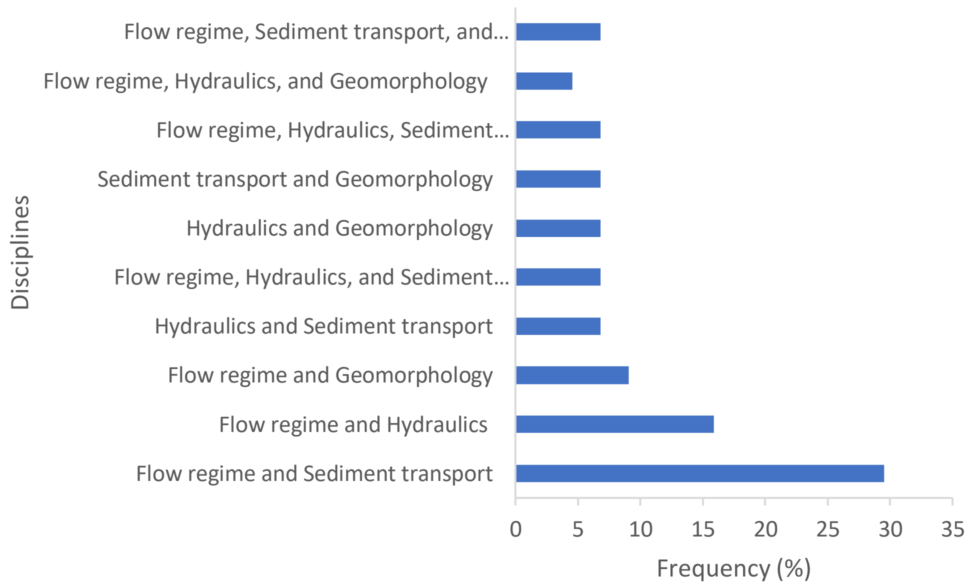

Figure 2.5 Frequency of different combinations of focus areas in the 82 published studies.

Figure 2.6 Geographic distribution of the study locations of the 82 reviewed articles. Further details are given in Table 2.3 (see letter code for each location). The latitudinal gradient of the locations ranged from 23°27'N to 23°27'S.

Table 2.3 River names and countries from each study; codes are those shown in Figure 2.6.

Code	River	Country
A	Grijalva River	Mexico
B	San Carlos River, Sarapiqui River, Tarcoles River, Puerto Viejo River, Toro River, Reventazón River	Costa Rica
C	Sinammary River	French Guiana
D	Tocantins River, Uatumã River, Janarú River, Curuá-Una River, Pitinga River, Araguari River	Brazil
E,F	Amazon Basin	Brazil
G	Jamari River	Brazil
H	Jauru River	Brazil
I	Cuiabá River	Brazil
J	Sa˜o Francisco River	Brazil
K	Grande River	Brazil
L	Paraná River	Brazil
M	Correntes River, Itajaí-Açu river	Brazil
N	Senegal River	Africa
O	Konkoure Estuary	Guinea
P	Niger River	Benin, Guinea, Mali, Niger, Nigeria
Q	Nakambe River	Burkina Faso
R	Volta River	Ghana
S	Tana River	Kenya
T	-	Tanzania
U	Kafue River	Zambia
V	Zambezi River, Insiza River	Zimbabwe
W	Lancang River	China
X	Red River	China, Vietnam
Y	Upper Mekong River, Wang River	Laos, China, Myanmar, Thailand
Z	Lower Mekong River	Laos, Thailand, Vietnam, Cambodia
A1	Mekong River, Da River	Vietnam
A2	Purari River	Papua New Guinea
A3	Brahmaputra River	India
A4	Sanaga River Basin	Cameroon

2.3.2. APPROACHES AND SCALES

Approaches used in the 82 papers were analysed using the framework provided by Kondolf and Piegay (2002). Most papers used more than one approach in their assessments (Figure 2.7). The most frequently employed approaches were from the sub-field of geomorphology, which included analyses of hydro-climatological time series data and field topographic measurements; some papers developed conceptual or system models to help understand impacts. Combinations of different tools can be found in papers such as Pickup (1980), Maingi and Marsh (2002), and Filho (2009). Measurements of flow, sediment transport processes and form dynamics (e.g. bedload, cross-sectional profiles, particle mobility, velocity, grain size) were less frequently used than might be expected. Only 18% of studies used these approaches to understand hydromorphic impacts; Stevaux et al. (2009) is an example of the use of such approaches, with authors collecting monthly bedload samples in the Upper Paraná River after closure of the Porto Primavera Dam (further details in Section 2.3.3).

Hydraulic modelling studies and a variety of remote sensing approaches (e.g. using satellite imagery) have been employed in published studies (48%). Their increasing prevalence in recent studies indicates that they are replacing field-based assessments where the goal of research has been to understand geomorphic processes and/or change. For example, Nguyen et al. (2015) used a quasi-2D cohesive sediment transport model to simulate sediment transport and deposition in the Mekong Delta, while Kameyama et al. (2013) used the MIKE SHE® and MIKE11® (Enterprise) models to understand seasonal changes in discharge and sediment transport of the Mekong River. Lauri et al. (2012) and Piman et al. (2013b) represent examples of the application of remote sensing approaches (further details below). Although remote sensing and modelling approaches are becoming more common, some of the first papers also used them, e.g. Pickup (1980) used the HEC-6® model to simulate the effect of a dam on sediment transport and erosion in the lower Purari River. A number of other hydrological models have been used, including WaterGAP Global Hydrology Model (WGHM®) in the study by Döll and Zhang (2010), Vmod by Räsänen et al. (2012), and the Soil and Water Assessment Tool (SWAT®) (Pitman et al., 2013).

The Mekong Basin is a clear research hotspot in SEA (22 of the 82 papers, 27%), with scientists from many countries collaborating on studies here. Lu and Siew (2006) examined the influence of Manwan Dam, the first of the upper Mekong cascade dams, on the sediment and hydrological regimes along the Lower Mekong River. This study used pre- and post-impoundment data. Kummu and Varis (2007) compared SSCs and sediment fluxes before and after the Manwan Dam closure in 1993. Piman et al. (2013a) and Piman et al. (2013b) modelled the effects of existing and future hydropower development in the Sesan, Srepok, and Sekong rivers using HEC-ResSim® and SWAT®.

The different spatial scales studied in published work were classified using the hierarchical framework provided by Frissell et al. (1986) (Figure 2.8a). Catchments can be defined as hierarchically organised systems incorporating, on successively lower levels, the catchment/basin, stream segment, reach, morphological unit, and microhabitat subsystems. Papers working at the whole catchment/basin scale were most frequent (35 papers, 43%), followed by river segment (21 papers, 26%) and reach scales (12 papers, 15%). No papers addressed only the morphological unit or microhabitat scales. For the larger scales, most papers dealt only with a single location – e.g. a single catchment or single segment. Thus, very few studies compared impacts across catchments or between segments. Most reach scale studies included multiple reaches.

Catchment scale studies were generally based on satellite data and involved modelling, either of water quality or biological responses, assessment of land use, flow or sediment flux changes (e.g. Gunkel et al., 2003; Mumba and Thompson, 2005; Lu and Siew, 2006; Kummu et al., 2010). Lauri et al. (2012), Piman et al. (2013a) and Piman et al. (2013b) incorporated remote sensing data in their studies to assess the cumulative impact of hydropower construction on the hydrology of the Mekong Basin; the former involved using satellite data to develop a distributed catchment hydrological model.

Most papers were post-dam studies, with most of them assessing hydrological alteration (Figure 2.8b). These studies were conducted at an average of 20 years after dam construction; the shortest period was one year after construction (Capo et al., 2006) and the longest was 47 years (Godinho et al., 2007). Only 29 papers (35%) included both pre- and post-dam data, with these assessing changes in discharge, bank erosion, flood pulses, bedload transport, suspended sediment load and bedform dynamics (e.g. Maingi and Marsh, 2002; Stevaux et al., 2009; Zeilhofer and de Moura, 2009). The study by Amenuvor et al. (2020) on the Volta River, Ghana is a rare example of a long-term analysis; it was based on pre- and post-dam datasets extending from 1936 to 2018.

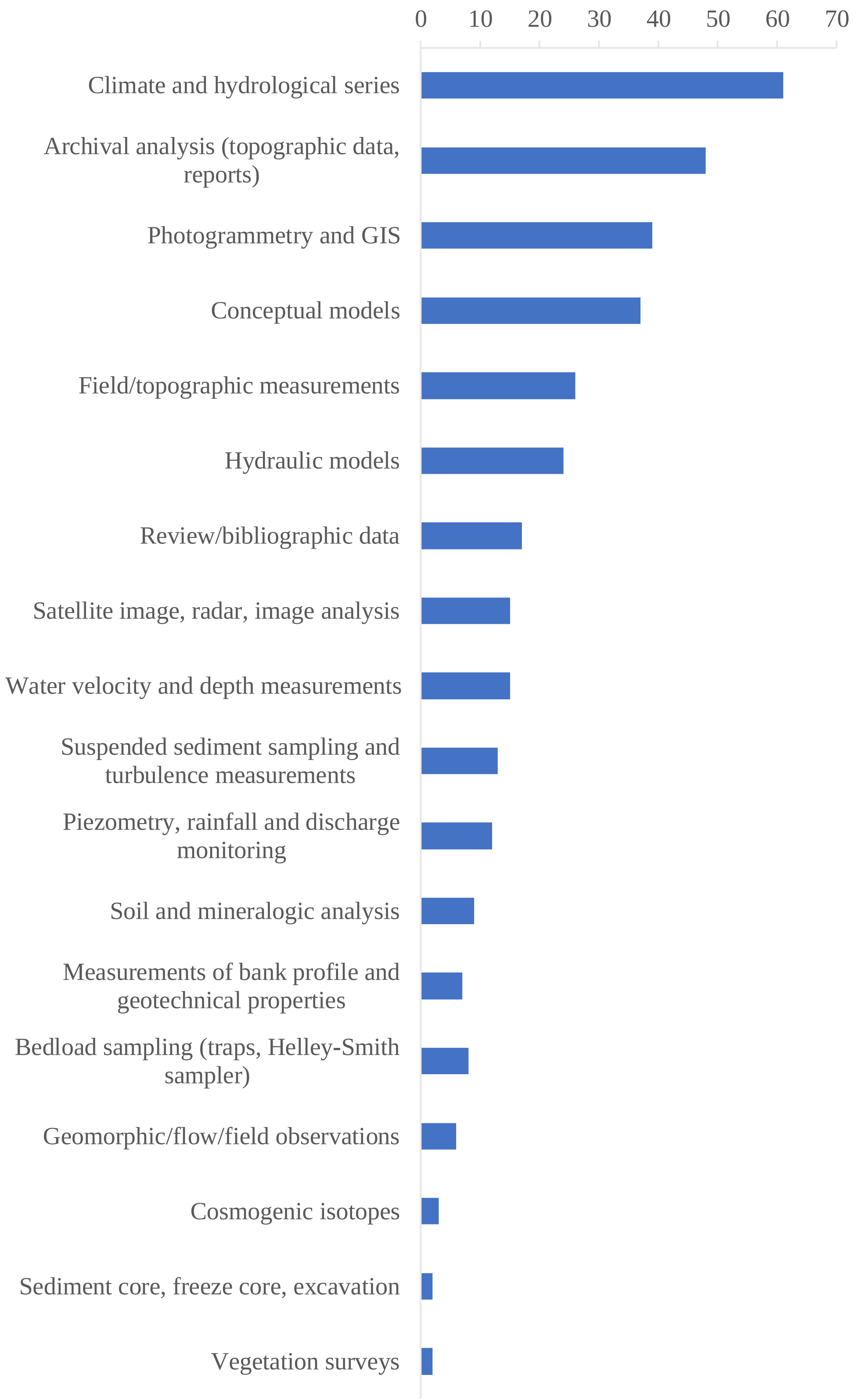

Figure 2.7 Frequency (number) of analytic tools distinguished from the reviewed papers. N.B. Several papers used more than one tool (see text for details).

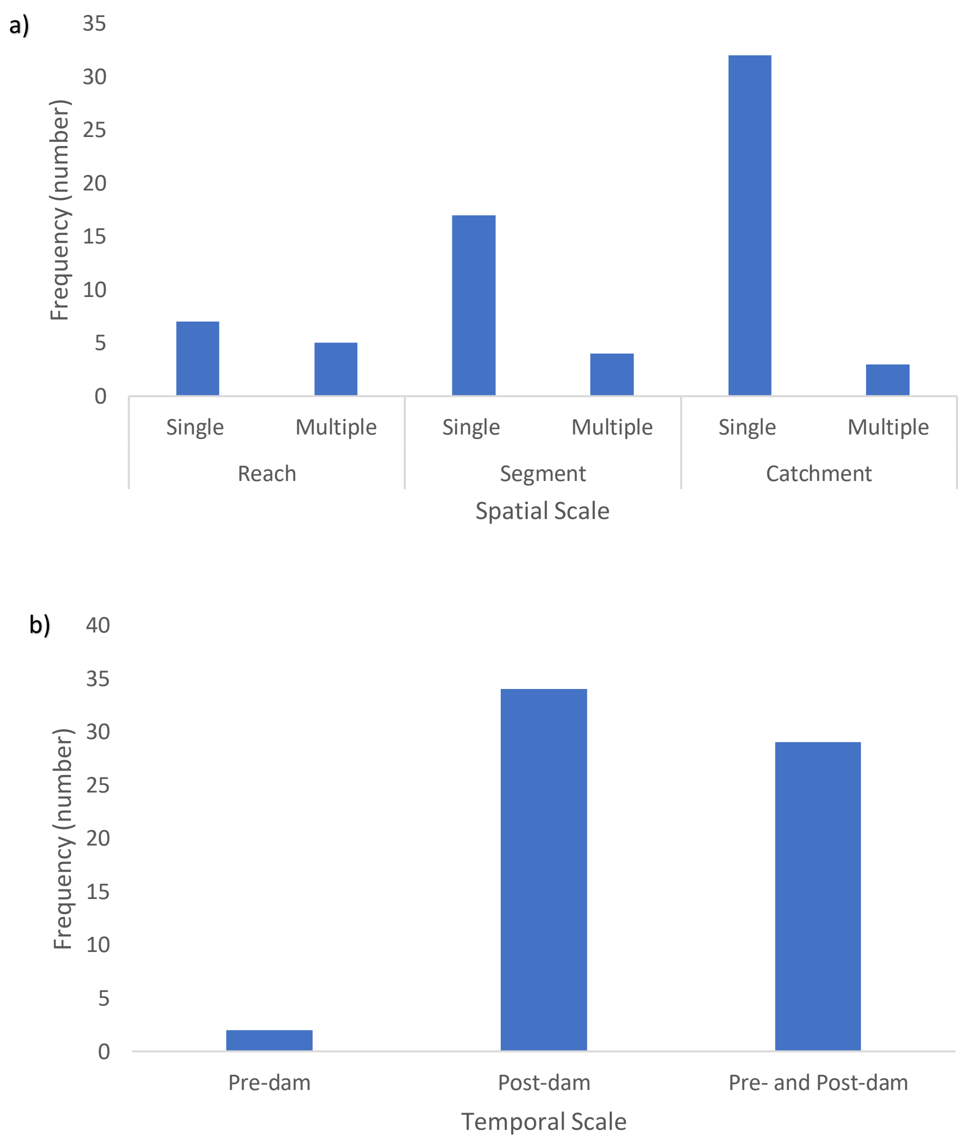

Figure 2.8 (a) Frequency of the different spatial scales addressed in the 82 studies, classified using the hierarchically organised systems framework provided of Frissell et al. (1986); (b) frequency of the different temporal scales addressed in the studies.

2.3.3. Hydromorphological Impacts

Figure 2.13 represents a synthesis of published studies, summarising types of impact observed in tropical systems and giving some specific examples for each impact. Impacts extend from hydrological and associated hydraulic change, to changes in transport of fine and coarse sediment, and ultimately to geomorphic adjustments in the downstream river. Details of each of these are given below.

2.3.3.1 Hydrological and Hydraulic Change

Dam construction tended to lead to clear decreases in peak discharge, moderate increases in low flows and an overall loss of seasonality in tropical river hydrographs; some studies reported reduced flood duration (Ponton and Vauchel, 1998; Lu and Siew, 2006; Kummu and Sarkkula, 2008; Zeilhofer and de Moura, 2009; Wu et al.,2009; Zhao et al., 2012; Kameyama et al., 2013; Ekandjo et al., 2018; Alcérreca-Huerta et al., 2019). Lu et al. (2014a) reported discharge being reduced appreciably in dry-seasons at Chiang Saen in the Mekong but reduced to a lesser degree in the wet-seasons. Figure 2.9 illustrates successive changes in the hydrograph of the Grijalva River following completion of a series of dams over a 50-year period. The main pattern was a reduction in seasonality, with successive dams also changing overall (average) flow magnitudes in different periods. Piman et al. (2013a) modelled how existing and future hydropower develop in the Sesan, Srepok, and Sekong Rivers changed flow regimes at critical points in the Mekong basin. The study showed that there was a 63% increase in dry-season flows, and a 22% decrease in wet-season flows at the outlet of the Mekong basin as a result of potential development of new dams (simulated for mainstem dams operating to maximise electricity production). Hydrological analyses of the Volta River by Amenuvor et al. (2020) also showed that inter- and intra-annual variations were much higher in the pre-dam period (Akosombo Dam, Ghana). Only 6 papers (10%) used the Indicators of Hydrologic Alteration (IHA) framework to help assess flow change in a systematic and comprehensive way (i.e. Maingi and Marsh, 2002; Lu et al., 2014a; Fantin-Cruz et al., 2015; Dang et al., 2016; Timpe and Kaplan, 2017; Chao et al., 2019). Across the papers that presented data, on average floods peaks were reduced by 28% (Abam, 1999; Maingi and Marsh, 2002; Stevaux et al., 2009; Lauri et al., 2012; Piman et al., 2013a; Ekandjo et al., 2018).

Few of the 82 studies looked into hydraulic effects in detail, either through field investigations, numerical modelling or physical experiments. Some (24 papers, 29%)

used hydraulic models such as HEC-RAS®, HEC-6®, MIKE SHE® and MIKE 11® (Enterprise), HydroGis® (developed by the Ministry of Natural Resource and Environment of Vietnam) to simulate the effect of dams on flow hydraulics and, in turn, sediment transport or erosion (e.g. Davies et al., 2000; Maingi and Marsh, 2002; Le et al., 2007; Tran et al., 2011; Piman et al., 2013a; Piman et al., 2013b; Kameyama et al., 2013; Arias et al., 2014). Stevaux et al. (2009) found that flow velocity in the Upper Paraná River changed from a pre-dam average of 0.88 m s^{-1} to 0.70 m s^{-1} during the construction of the dam, and to 0.56 m s^{-1} post-dam. Ponton and Vauchel (1998) showed that post-impoundment increases in maximum daily water velocity increased the risk of young fish being flushed away. This study was based on a 2-year dataset, one year before impoundment and one after. The modelling work of Logah et al. (2017) was able to identify threshold dam releases that created river stages sufficient to cause inundation of floodplain areas along the Lower Volta River.

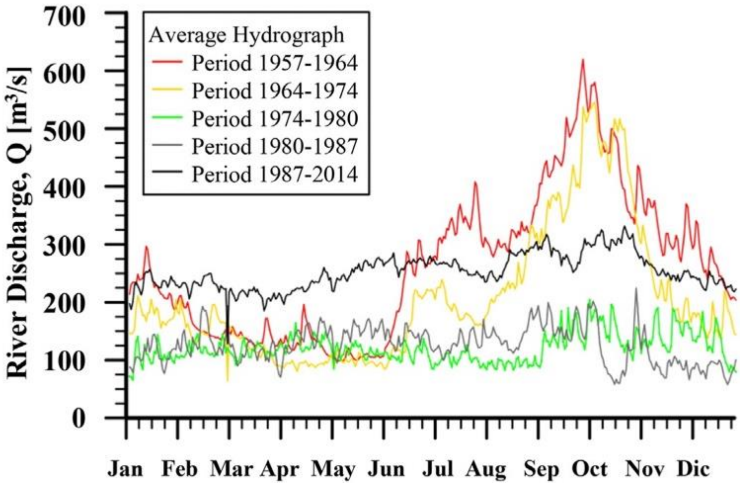

Figure 2.9 Average hydrographs during the periods before dams were constructed (1957–1964), after the starting operation of the first dam (1964–1974), second (1974–1980), third (1980–1987) and fourth dam (1987–2014) within the Grijalva River (Alcérreca-Huerta, 2019).

2.3.3.2. Sediment Dynamics, Loads and Budgets

Impacts of dams on sediment transport were assessed in several of the papers (e.g. Lu and Siew, 2006; Kummu and Varis, 2007; Le et al., 2007; Fu et al., 2008; Kummu et al., 2010; Kameyama et al., 2013; Kondolf et al., 2014; Lu et al., 2014b; Amenuvor et al., 2020). The simulations of Kameyama et al. (2013) showed that there was a moderate decrease in peak discharge during the rainy season and a corresponding increase in the subsequent months following dam construction. Changes to sediment transport paralleled these changes, with increased transport in the months after the rainy season. Amenuvor et al. (2020) showed that damming on the Volta River had more significant effects on the sediment load delivered to the delta than on river discharge (sediment load decreased by 92.3% and discharge by 23.2%).

Ten papers (12%) presented sediment load time series and/or concentration-discharge relationships (i.e. Vinh et al., 2014; Mamede, et al., 2018; Charoenlerkthawin, et al., 2021; Pickup, 1980; Brandt and Swenning, 1999; Capo et al., 2006; Fu et al., 2008; Kameyama et al., 2013; Liu et al., 2013; Amenuvor et al., 2020). Some examples showing post-dam alterations are given in Figures 2.10 and 2.11. Kameyama et al. (2013) reported that, in the Chiang Saen watershed, sediment transport in the post-rainy season months in 2002 (post-dam) increased compared to 1991 (pre-dam). Similarly, Liu et al. (2013) showed sediment load in the post-dam period initially increased but later decreased. Lu and Siew (2006) reported that sediment loads in Chiang Saen declined since the Manwan Dam began its operations in 1992.

Several papers reported changes in fine sediment fluxes and concentrations (e.g. Kummu and Varis, 2007; Dang et al., 2010). The general pattern has been for reductions in fine sediment loads, as illustrated in Figures 2.10-2.12. Lu and Siew (2006) found a reduction in monthly SSC of 40% or more at several gauging stations in the Lower Mekong River after the closure of Manwan Dam. Kummu and Varis (2007) estimated that the annual sediment flux in the Lower Mekong has been more than halved (from 70×10^9 kg to 31×10^9 kg) since completion of Manwan Dam. Discharge-SSC relations have been affected by damming, both in terms of the slope and positions of fitted regressions; for a given discharge, SSCs were typically reduced after damming, although the magnitude of effects differed between locations. Effects of damming on seasonal patterns of SSC differed between locations, with e.g. the greatest change occurring in August and January in Pakse, and October and June in Chiang Saen (Figure 2.11).

According to Kummu and Varis (2007), no reliable data on bedload are available for the Mekong Basin. Only two papers had looked at bedload grain sizes (i.e. Stevaux et al., 2009; Logah, 2017), and none computed bedload transport rate. Thus, it is very hard to draw any firm conclusions about impacts of tropical dams on bedload.

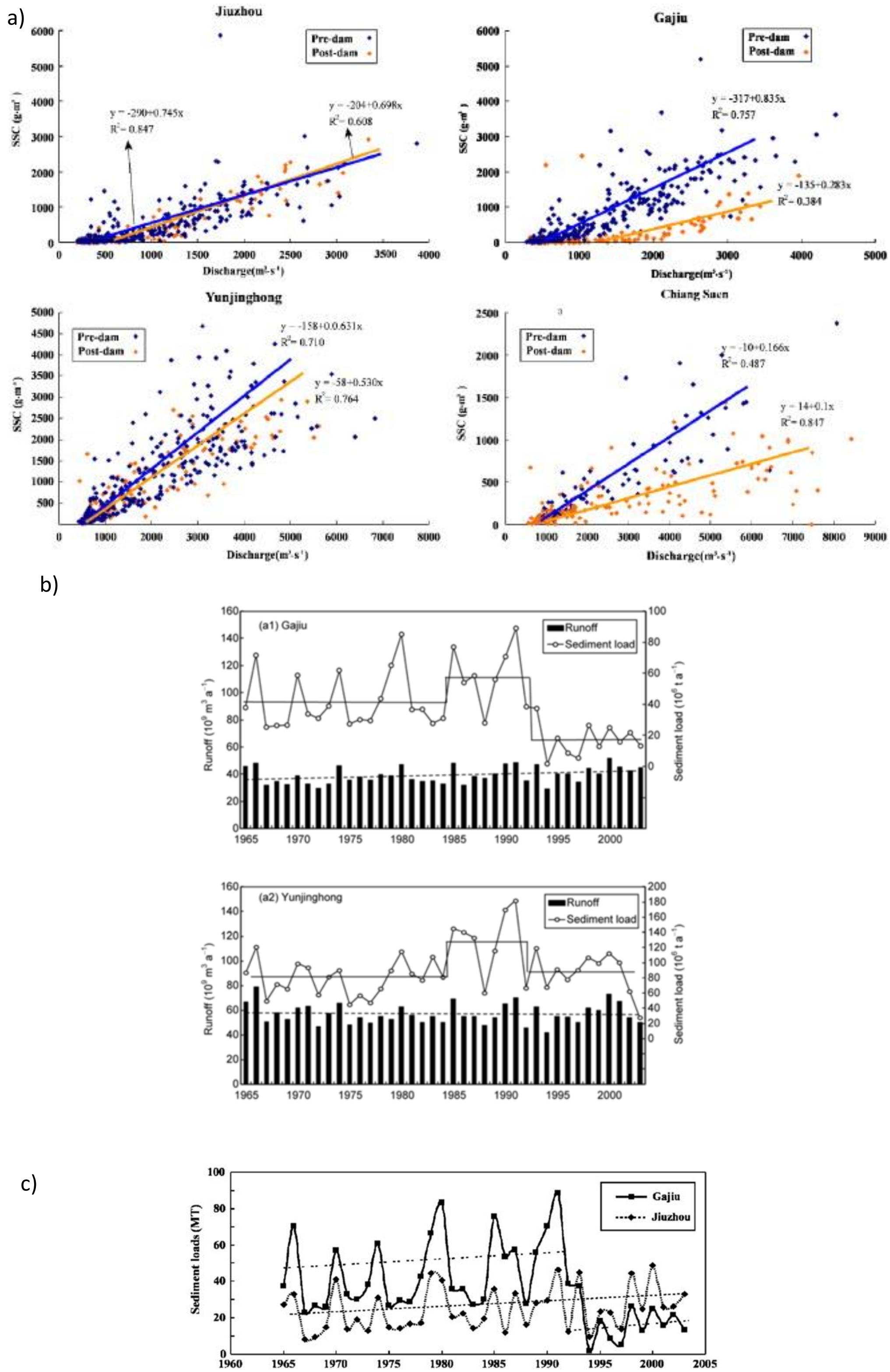

Figure 2.10 (a) Suspended sediment concentration plotted against the discharge in Upper Mekong (Lancang) River (Fu et al., 2008); (b) Annual runoff and sediment load of the Lancang River (Liu et al., 2013); (c) Comparison curves of 1965–2003 synchronous sediment loads at Jiuzhou and Gajiu stations on Lancang River (Fu et al., 2008).

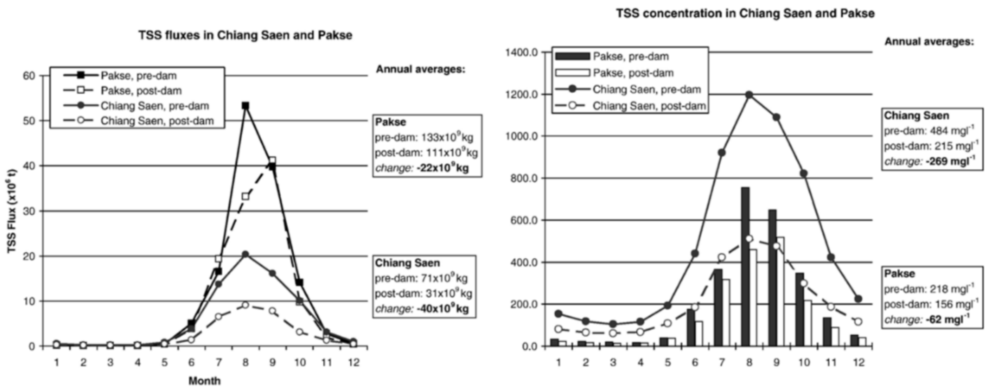

Figure 2.11 Total suspended sediment fluxes (left) and concentrations (right) at Chiang Saen and Pakse (Kummu and Varis, 2007).

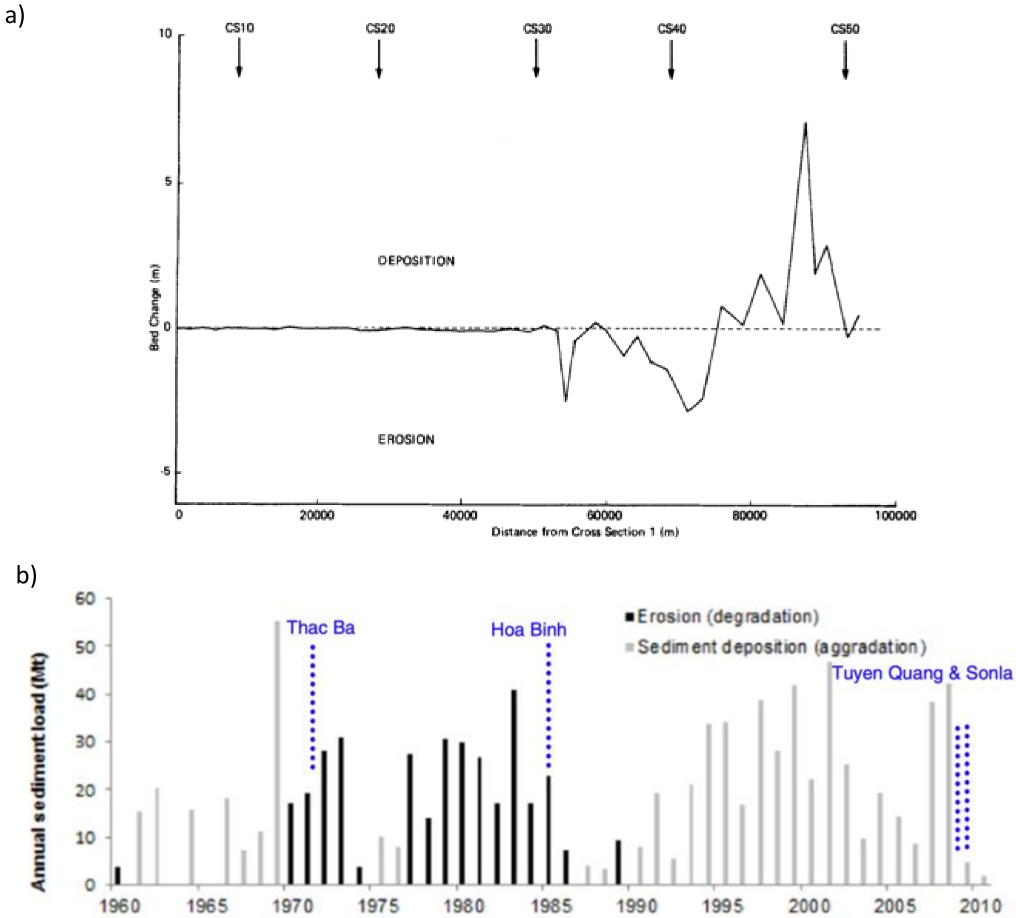

Figure 2.12 (a) Local erosion and deposition (Pickup, 1980); (b) Annual erosion and deposition affected by the dams in the studied reach of the Red River (Lu et al., 2015).

2.3.3.3. Geomorphic Change

Reported geomorphic effects include bed armouring, bank erosion, spatially and temporally variable patterns of bed scour and aggradation, and changes in bedform morphology. Pickup (1980) and Lu et al. (2015) showed longitudinal patterns of scour and fill (Figure 2.12). The hydraulic model of the former author showed that the sandy reach of Purari River had a tendency to scour but most of this sediment was redeposited in wider sections of river further downstream. Lu et al. (2015) found that before construction of the first dam (Thac Ba), deposition was dominant in the lower reach of the Red River; however, after dam construction the dominant process changed to erosion (amount of erosion changed from 3.7 and 40.9 metric tons per year), attributed to 'hungry water' effects (as per Kondolf, 1997). However, after the second dam closure (Hoa Binh), deposition processes again became dominant (Figure 2.12).

Most sedimentary adjustments during the transition phase (i.e. river shifting to a new regime state) happen in the first few years of dam operation (Petts and Gurnell, 2005). Pickup (1980) and Lu et al. (2015) suggested that due to bed-armouring, limited erosion will occur and rivers will move towards a new state quite rapidly. Stevaux et al. (2009) reported that reduced downstream flows in the Paraná River due to the filling of the reservoir led to a decline in bank erosion immediately after the dam closure. However, the rates of erosion in the following period increased by more than 230%, even though discharge was similar to that before dam closure. Amenuvour et al. (2020) reported that the Volta River Delta underwent severe erosion after dam closure due to the reduced sediment supply, but subsequently the delta established a quasi-equilibrium state. Their study was based on a long term pre- and post-dam dataset (1936 to 2018).

Temperate river studies have helped elucidate the controls on armouring and its dynamics in impounded rivers. Vericat et al. (2006b) for example, showed the effects of successive floods on the breakup of the armoured bed of the Lower Ebro, and its reestablishment during inter-flood periods. Increased armouring has also been identified in other temperate rivers such as the Han (Danjiangkou Reservoir, China) and Yellow (Sanmenxia Reservoir, China) rivers, 4 to 6 years after dam closure in reaches located 25 to 30 km downstream (Chien, 1984). None of the reviewed studies empirically assessed changes in armouring downstream from tropical dams.

Figure 2.14 compares damming and associated flow pattern change in rivers across major climate regions. The diagram has been produced using data provided in some of the papers included in this review, as well as others that concern dams in the Mediterranean and temperate regions (based on data provided by Benjamin and Van Kirk, 1999; Maingi and Marsh, 2002; Batalla et al., 2004; Kondolf and Batalla, 2005; Yang et al., 2008; Stevaux et al., 2009; Zeilhofer and de Moura, 2009; Ronco et al., 2010; Chen et al., 2010; Zeug et al., 2011; Lu et al., 2014; Wang et al., 2015; Chen et al., 2015; Timpe and Kaplan, 2017; Ekandjo et al., 2018; Chao Thi et al., 2019; Villablanca et al., 2021). Impoundment Ratio (IR) is the ratio between dam storage capacity and the natural mean annual catchment runoff (Batalla et al., 2004); it provides a metric of how much of the mean annual runoff may be impounded and gives an estimation of the mean residence of the water in the reservoir. The correlation coefficient between mean monthly flows pre- and post-dam provides a metric of how much the regulated flow regime (post-dam) differs from the natural one (pre-dam). Correlations 1 or close to 1 indicate no or very little change in monthly flow patterns. The diagram shows that tropical rivers have a combination of rather low IR (mostly less than 0.5), and high and positive correlations (mostly above 0.75). Thus, topical dams appear to impound relatively little of the basin runoff (less than 50%) and produce a regulated regime that differs rather less from the natural one than often seen in other regions. Those in the Mediterranean system have the highest IRs (in some cases more than 100% of the annual runoff), with some having negative correlation coefficients which indicate a reversal in the magnitude of seasonal flows. None of the tropical rivers had such reversals. Such differences are potentially significant from an ecological perspective, given the importance of flow timing, but there is a need to be cautious with inferences drawn from Figure 2.14. Since few studies provide the required data, sample sizes are generally low and differ between regions; it may be, for instance, that the apparent variability of Mediterranean systems is simply due to the larger sample size.

2.3.3.4. Sediment Connectivity

Much of the research detailed above are either implicitly or explicitly dealt with issues of longitudinal connectivity. There has been a number of major reviews of the influence of dams on rivers set within the context of connectivity. For instance, Grill et al. (2019) assess the connectivity status of 12 million km of rivers globally and identify those that remain free flowing for their entire length. The authors apply a new method to quantify riverine connectivity and map free flowing rivers to provide a foundation for concerted global and national strategies to maintain or restore them. Moreover, Stanford and Ward (1983) first developed serial discontinuity concept (SDC) as a theoretical construct that views impoundments as major disruptions of longitudinal resource gradients along river courses, it was then extended to include the dynamics of alluvial floodplain rivers into the model using a three-reach characterisation: constrained headwater reach, braided reach and meandering reach (Ward and Stanford, 1995).

The importance of lateral connectivity has been recognised for the last two decades, and has been discussed in both hydrological, geomorphic and ecological terms (e.g. Tetzlaff et al., 2007). In catchment hydrology, isotope studies have been able to shed much new light on sources of channel water, water flow paths and water transit times (Tetzlaff et al., 2014; Soulsby et al., 2015). Another major focus area has been on river-floodplain connectivity. Several studies documented the importance of permanently connected, artificial floodplain waterbodies as spawning, feeding, nursery (growth) and refuge areas (Simons et al., 2001; Grift et al., 2003; Jurajda et al., 2004; Nunn et al., 2007).

The rehabilitation of degraded rivers is therefore recognised as needing to involve reinstating a range of lateral hydrological connectivity and thus the ecological processes of the river–floodplain ecosystem (Ward et al., 1999; Morley et al., 2005). Some dam operational programs include flows designed to create overbank flows and thus connect rivers to their floodplains; such flows can be seen as 'functional' (Cowx and van Zyll de Jong, 2004; Wolter, 2010), designed to recreate floodplain habitats with a range of connectivity as typically observed in a natural riverscape (Bolland et al., 2012).

As tools and approaches capable of assessing hydrological connectivity have evolved and been applied (e.g. isotope based ones), others to better understand sediment connectivity between coupling between stream channels and their catchments have been developed. According to the literature, there are three approaches which can be adopted in assessing sediment connectivity: empirical (Borselli et al., 2008), modelling (Liu and Fu, 2016), and conceptual (Bracken et al., 2015). A few examples of these include Index of Connectivity (IC), sediment delivery ratio (SDR), spatially distributed models such as WATEM-SEDEM (Liu and Fu, 2016), LAPSUS (Baartman et al., 2013), WASA-SED (Medeiros et al., 2014), HEC-RAS® (Karim et al., 2016) and SEED (Di Stefano and Ferro, 2018) have also been generally applied.

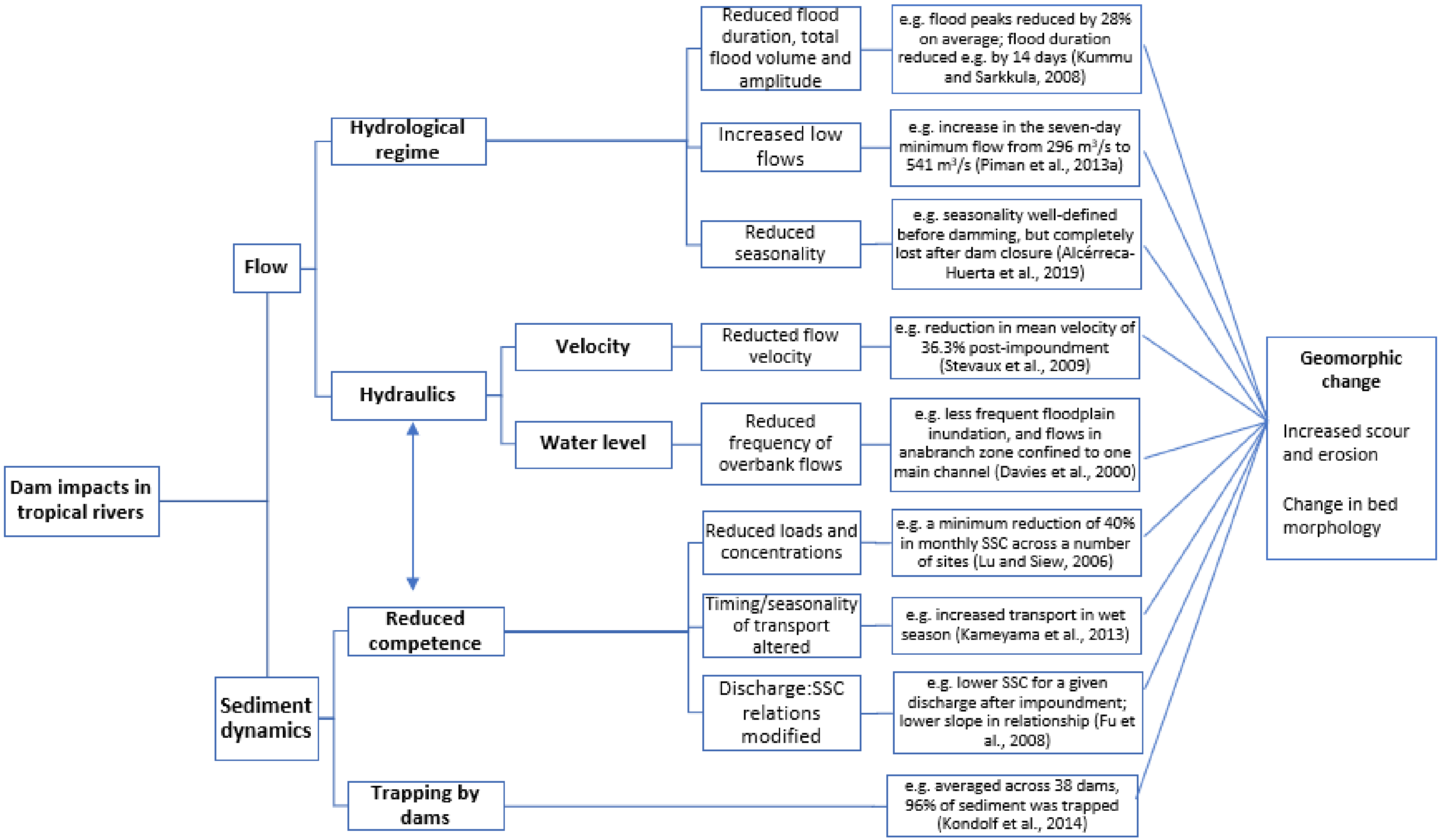

Figure 2.13 Overview of the hydromorphic changes observed in tropical rivers following impoundment. The right-hand column gives examples of each specific type of change.

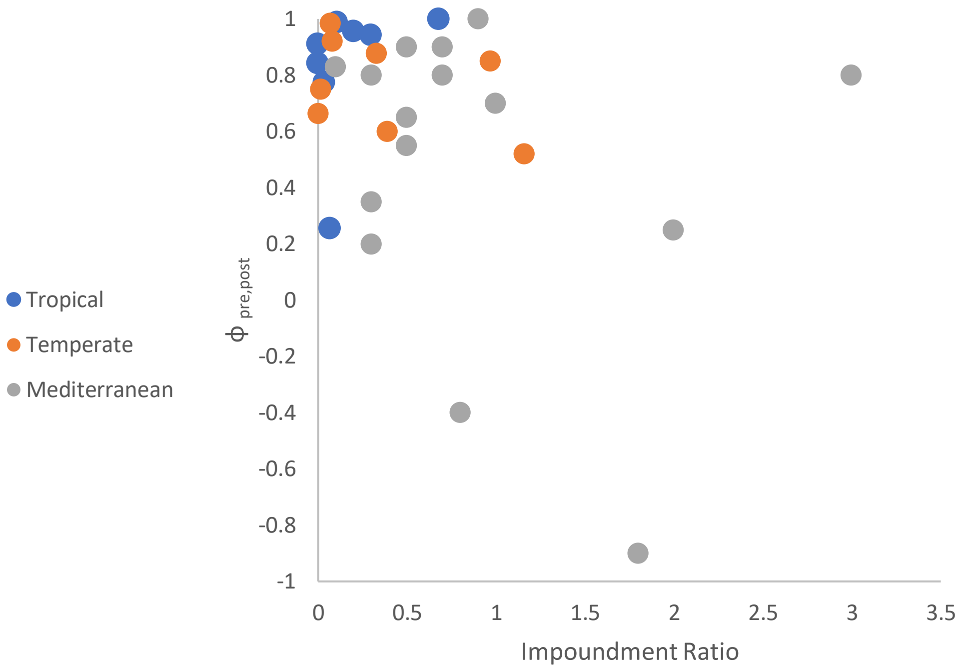

Figure 2.14 Relations between impoundment ratio (IR) and change in monthly flow series following impoundment in rivers across three major climate regions. IR is defined in the main text. Changes in flow series are evaluated by means of a correlation coefficient between respective mean monthly discharges pre- to post-regulation ($\varphi_{pre,post}$), which allows determination of the degree of alteration of the flow pattern (after Batalla et al., 2004).

2.4. Discussion

A systematic search of peer-reviewed published literature revealed a total of 82 papers detailing flow and/or geomorphic changes in dammed rivers in the world's tropical regions. This is a relatively small number considering the scale of dam building in the tropics and the global significance of tropical regions for biodiversity (Dudgeon et al., 2006). The 82 papers allow us to draw some very broad, general conclusions about the nature of responses to impoundment in tropical systems. At this broad level, responses are similar to those reported in other climate regions (Figure 2.15): (i) reductions in flow variability and seasonality are typically observed in tropical rivers, as a result of reductions in peak and increases in minimum flow, (ii) reductions in sediment loads related to both supply limitation (trapping by dams) and reductions in competence are commonly reported, and (iii) bank erosion and bed scour are frequent in tropical rivers and, as in other regions, have been attributed to 'hungry water' (Kondolf, 1997).

The number of studies in tropical regions is, however, insufficient to determine whether some more specific aspects of river response to impoundment differ consistently between tropical rivers and those in other regions. Very few studies assessed changes in bedload in tropical rivers, and this limits opportunities for comparison. Also, the lack of long term, pre- and post-dam studies in the tropics mean that it is hard to know whether relaxation times (i.e. time to reach a new, adjusted state) are consistently different. While a small number of tropical river studies have looked at the temporal sequence of changes following dam closure (e.g. Stevaux et al., 2009), these either did not explicitly determined relaxation time or were not conducted over a long enough period to establish that the new regime state had been reached. Amenuvour et al. (2020) is one of the few studies to report on a new, quasi-equilibrium regime state but this work concerned a delta. It therefore remains hard to test whether any of the regional differences in river channel relaxation time hypothesised by Petts and Gurnell (2005) are borne out by empirical data. Similarly, while the relatively high runoff rates and sediment yields in tropical catchments (Figure 2.3a) lead to hypotheses about how the downstream distance needed for channels to recover may differ from that in other regions (i.e. shorter distance due to greater inputs from tributaries), none of the studies explicitly addressed this point. It therefore remains hard to provide clear evidence of consistent differences in specific, detailed responses to impoundment between tropical and other climate regions. Such comparisons are also hampered by marked within-region variation in the design and operational characteristics of dams, and more generally by scale issues (e.g. comparing between rivers of different size is problematic). This scale issue also influences what can to infer from between-region analyses of natural hydrological regimes, unless river size is factored in.

The review indicated that tropical dam impact studies have used a wide range of tools and approaches. However, given that we are currently in an era of big-data acquisition and semi automation of geomorphic/hydrologic surveys, it is notable that some tools that would be extremely insightful have yet to be widely adopted in tropical settings. For example, no studies have routed high resolution, repeat survey topographic data through systematic methods such as Geomorphic Change Detection (GCD) tool (available at http://gcd.riverscapes.xyz) (Wheaton, 2015) to help qualify topographic and/or morphological change after impoundment. Similarly, systematic assessments of flow change are possible using the Range of Variability approach (Richter et al., 1997) and associated the Indices of Hydrological Alteration (IHA) framework (Richter et al., 1996), but these have rarely been applied to tropical rivers. These assessments would be particularly useful for understanding which aspects of the flow regimes of tropical rivers have been most affected.

Eleven of the reviewed papers (13%) dealt explicitly with flow management strategies aimed at mitigating dam impacts. Two of these papers discussed strategies to mitigate impacts on river biogeochemistry: Viana (2002) discussed how selective withdrawal from different reservoir depths helped limit impacts on oxygen and temperature, while Kunz et al. (2013) used the Itezhi-Tezhi Reservoir, Zambia, as a model system to design optimized operational procedures to prevent hypoxia and to relieve low-nutrient conditions in the Kafue Flats floodplain. Other studies focused more explicitly on ecological considerations. For example, Zeilhofer and de Moura (2008) focused on developing dam operation policies to mimic natural events considered important for conserving the Cuiabá River floodplains in the Pantanal, Brazil, while Fantin-Cruz et al. (2015) proposed flow management to help maintain the seasonal flooding regime of the Correntes River. Other examples of ecologically oriented flow management include the work of Godinho et al. (2007) who used a model of water releases to enhance fisheries on the Sao Francisco River below Tres Marias Reservoir. It is notable that of the 11 papers that dealt with flow management, only two considered geomorphic processes (i.e. Abam, 1999; Basson, 2004). This contrasts with temperate systems where there are numerous examples of functional flows designed for geomorphic purposes (e.g. Hughes and Rood, 2003; Corenblit et al., 2009; de Jalón et al., 2017; Hayes et al., 2018).

One issue that has rarely been assessed in tropical catchments is the interaction of landcover change and damming. While catchment deforestation contributes to the high suspended sediment concentrations seen in many tropical rivers, the trapping of fine sediments by dams will interrupt the downstream conveyance of this material, limiting reservoir capacity and reducing loads downstream. Thus, there are likely to be complex downstream patterns in suspended load as a result of the interaction of these two factors, especially where unregulated tributaries contribute new material. Assessments of sediment connectivity would be particularly useful, and tools are available now to do this at the whole catchment scale (e.g. Index of Sediment Connectivity; Borselli et al. (2008) and Cavalli et al., (2013)). As it is possible to quantify fine sediment remotely (Isidro et al., 2018), or apply catchment models such as SWAT® or TETIS® (Arnold and Fohrer, 2005; Frances et al., 2012) to simulate downstream changes in suspended sediment loads, such studies would be particularly useful in tropical catchments to help direct forest clearance to areas where impacts on mainstem fine sediment loads are limited. Studies that consider landcover change and it impacts on flow and fine sediment in topical rivers will also be valuable for elucidating spatial patterns of relaxation, and the time taken to reach an adjusted regime state.

Dams interrupt sediment conveyance and so can disconnect up and downstream river sections. The associated flow change, depending on dam operations, may further add to disconnectivity by creating hydraulic conditions that limit dispersal of organisms. For instance, inappropriately low compensation flows may create long hydraulic dead zones that limit dispersal of drifting aquatic insects, as observed for weirs (Brooks et al., 2018). Hydraulic studies focussed simply on assessing microhabitat suitability *in situ*, rather than considering the importance of dispersal for population dynamics, run the risk of underplaying impoundment impacts. Thus, studies able to consider flow hydraulics along extensive river sections should be included as part of dam impact assessments.

In general, assessments of geomorphic integrity in tropical rivers are less common than those focussed on ecological or human needs. This is paradoxical as geomorphic processes and conditions shape the aquatic habitat that influences ecological diversity and the ecosystem services that stem from this diversity. Comprehensive and continuous long-term studies of geomorphological change, spanning pre- and post-dam periods, remain scarce in the tropics – most papers included in this review were based on short series of data (1-2 years) before or after impoundment, and very rarely both. The absence of long-term studies is a problem because it can then be hard to scale observed dam effects according to natural inter-annual variability. Nevertheless, it is clear from the review that tropical dams cause alterations to flow magnitude, variability and timing, elements of the flow regime that are critically important for river geomorphic and ecological integrity. There is much to be gained from long-term hydromorphic studies of tropical rivers, to better understand how fundamental aspects of their character might influence how they respond to damming, and to provide the evidence base needed for designing functional flows.

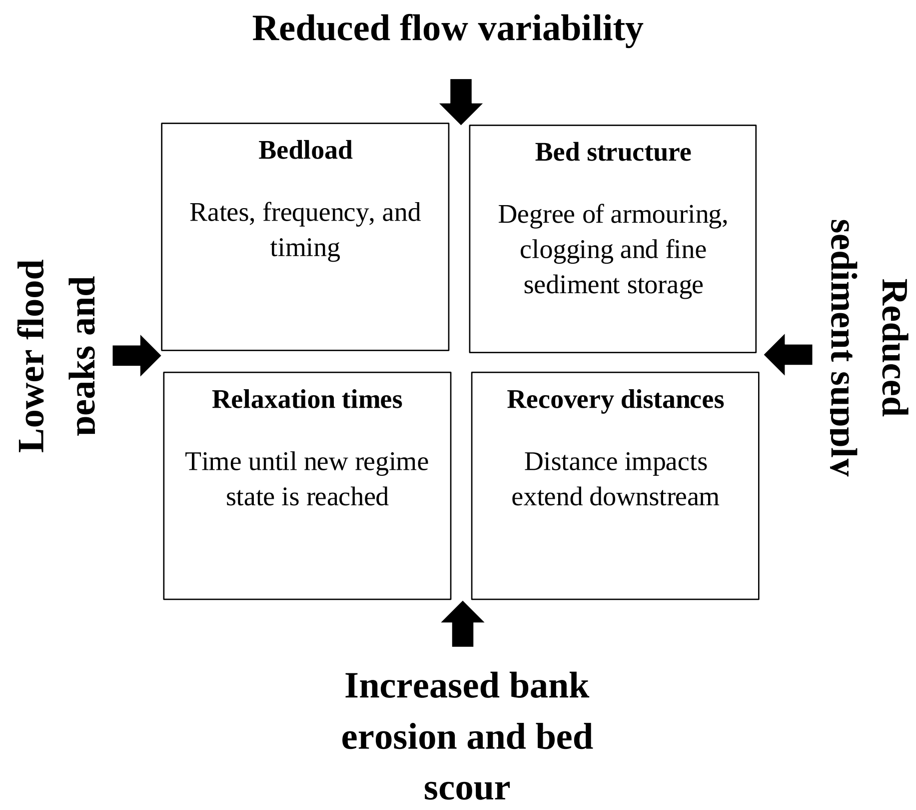

Figure 2.15 Conceptual overview of our understanding of the impacts of dams on tropical rivers. The outer phrases (bold text) summarise known general responses to damming that are consistent across climate regions. The central boxes each represent an aspect of change that may differ in detail between regions, but which has yet to be addressed in tropical rivers to the extent needed for comparison between climate regions.

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APPENDIX A: Search string

TITLE-ABS-KEY ("Southeast Asia" OR "South East Asia" OR tropic* OR "tropical region*" OR mexico OR belize OR "Costa Rica" OR "El-Salvador" OR guatemala OR honduras OR nicaragua OR panama OR brazil OR colombia OR ecuador OR "French Guiana" OR guyana OR paraguay OR suriname OR venezuela OR anguilla OR "Antigua and Barbuda" OR aruba OR bahamas OR barbados OR "British Virgin Islands" OR "Cayman Islands" OR cuba OR "Dominican Republic" OR grenada OR guadeloupe OR haiti OR jamaica OR martinique OR montserrat OR "Netherlands Antilles" OR "Saint Vincent and the Grenadines" OR "Trinidad and Tobago" OR "Turks and Cacaos Islands" OR "United States Virgin Islands" OR angola OR cameroon OR "Central African Republic" OR congo OR "Equatorial Guinea" OR gabon OR zambia OR burundi OR kenya OR madagascar OR mozambique OR tanzania OR benin OR "Burkina-Faso" OR "Cote d'loire" OR ghana OR guinea OR liberia OR mali OR nigeria OR "Saotome and Principe" OR senegal OR "Sierra Leone" OR togo OR brunei OR myanmar OR cambodia OR "East Timor" OR indonesia OR laos OR malaysia OR borneo OR philippines OR singapore OR thailand OR vietnam OR "Sri Lanka" OR india) AND TITLE-ABS-KEY (dam OR dams OR "large dam" OR "large dams" OR "small dam" OR "small dams" OR weir* OR "dam reservoir*" OR impoundment) AND TITLE-ABS-KEY ("dam impact*" OR "dam effect*" OR "dam implication*" OR "downstream effect*") AND (hydrology OR morphology OR geomorphology OR hydrogeom orphology)

CHAPTER 3

A Framework for Hydrological Characterisation to Support Functional Flows (HyFFlow): Application to a Tropical River

3. A FRAMEWORK FOR HYDROLOGICAL CHARACTERISATION TO SUPPORT FUNCTIONAL FLOWS (HYFFLOW): APPLICATION TO A TROPICAL RIVER

ABSTRACT

Study region: Sarawak, Malaysia.

Study focus: This chapter presents a framework ('HyFFlow') designed to provide a systematic characterisation of river flow regimes. HyFFlow consists of four packages, together yielding information on rainfall and flow patterns. They include analyses to identify and characterise different types of high flow event, based on their magnitude, shape and duration, and assessment of the timing and duration of periods of high and low flow. HyFFlow also includes assessment of temporal patterns (seasonality and long-term trends) in rainfall and flow. The characterisation provides a comprehensive baseline against which future changes can be assessed.

New hydrologic insights for the region: HyFFlow analyses indicated subtle and complex changes to long-term hydro-climatological conditions in the Baleh catchment, Malaysia: (i) analyses of the hydrograph indicated that there have been reductions in flow in the wet season, but not at other times of the year, and (ii) while there is no evidence of long-term trends in precipitation across the catchment (no change in monthly rainfall values over a 51-year period), there has been an increase in the number of days each month with no rainfall in some sub-catchments. HyFFlow analyses also identified four main types of high flow event in the Baleh whose functional roles need to be assessed as part of future geomorphic and ecological studies.

3.1. INTRODUCTION

Maintaining natural flow variability has become a central tenet of the science related to sustainable river and catchment management, and to environmental flows (e-flows). This science can be traced back several decades, from the early work on compensation and minimum-maintained flows undertaken on the River Tees in UK (Armitage, 1977) through PHABSIM (Milhous et al., 1984) and related habitat models such as Meso-HABSIM (Parasiewicz, 2001), to the more holistic tools now used to support flow management in regulated rivers (e.g. DRIFT: King et al., 2003; Benchmarking: Arthington, 1998). The development of the natural flow paradigm (Richter et al., 1997) has been pivotal to the evolution of this science, with flow variability now seen as critical for maintaining both the physical and ecological integrity of streams and rivers.

The last few years have seen the emergence of so-called functional flows (FFs) within the e-flows literature (Yarnell et al., 2015). The ideas that are central to FFs have been around for some time, but their formalisation has helped crystalise the notion that specific flows are needed to support specific functions, whether related to ecology (e.g. upstream movement of salmonids during the pre-spawning season; Malcolm et al., 2012), geomorphic processes (e.g. Batalla and Vericat, 2009; Meitzen et al., 2013), or for socio-economic purposes (e.g. Bruwer et al., 1996; Barbier and Thompson, 1998; Richter, 2010; Postel and Richter, 2012).

The fundamental ideas related to e-flows and FFs are applicable to any river system, but the challenges of developing them vary significantly from place to place. To date, FFs have been developed largely in regions with marked seasonal patterns of flow variability which have resulted in strong temporal rhythms to species' life cycles and ecosystem processes (e.g. Yarnell et al., 2015; Hayes et al., 2018; Palmer and Ruhi, 2019). In Mediterranean regions, for example, rivers may have very little or even no flow during the dry summer months (Garcia et al., 2017); this seasonal rhythm influences the timing of sediment transport and associated channel change (Church, 1995) as well as species phenologies (Alvarez and Pardo, 2005). In contrast, tropical rivers are strongly monsoon-driven; their hydrological regimes reflect patterns of rainfall magnitude and timing that differ from those in temperate and Mediterranean regions, but also the much higher runoff coefficients of tropical catchments (Chong et al., 2021).

Comprehensive ways of interrogating river flow data are of great value for helping to understand fluvial and ecological dynamics, but are especially important in the tropics to help tease out any subtle or complex temporal rhythms that exist (e.g. Wohl et al., 2012; Ghosh and Guchhait, 2016; Lazaro-Vazquez et al., 2018), and to provide the comprehensive descriptions of baseline conditions that are needed as the starting point for setting e-flows and FFs. A number of approaches and indices for hydrological characterisation exist. These were recently reviewed by Jumani et al. (2020) who separated indices into those which are descriptive, and those which are prescriptive. Descriptive indices provide a characterisation of the flow regime, while prescriptive ones focus on recommending specific flows or flow regimes as part of e-flows or FFs. Most existing approaches are prescriptive (Jumani et al., 2020) and while the descriptive ones that exist are useful, they each tend to focus only on one or two aspects of the hydrograph (e.g. variability) rather than multiple traits simultaneously. Thus, there remains scope for more comprehensive ways of analysing flow series, bringing together features of several existing indices and approaches to improve characterisation of hydrological regimes.

This chapter presents a structured framework to help understand multiple aspects of river hydrological regimes and support flow management in regulated rivers. The framework (Hydrological characterisation to support Functional Flows (‘HyFFlow’)) yields a characterisation of flows over several timescales and brings together a variety of complementary analytical methods and descriptors. Many of the descriptors used within HyFFlow have been found to be ecologically relevant (e.g. multiples of the median flow that influence invertebrate community structure; Gibbins et al., 2001) and/or are recognised as being important for geomorphological processes (e.g. the shape and magnitude of high flow events). Thus, while on its own, HyFFlow cannot be used to set e-flows or FFs (i.e. it cannot assess ecological or geomorphological functions or needs), it provides a description of the flow regime that is based on traits known to influence physical and ecological processes. Therefore, HyFFlow can be used in two ways: (i) to provide a holistic characterisation of the flow regime against which future changes can be assessed, (ii) to identify particular aspects of the hydrograph whose specific ecological and/or geomorphic function needs to be assessed, to support development of functional flows.

HyFFlow is applied here to the Baleh River, a meso-scale catchment on the island of Borneo, Malaysia. A hydroelectric dam is currently being constructed on the Baleh (due for completion in 2026) but like many tropical rivers, limited ecologic and geomorphic data exist. Comprehensive analysis of existing flow data is therefore important to understand pre-dam, baseline conditions in as much detail as possible, and specifically to provide information on flow traits whose functional significance can become the focus of subsequent geomorphic and ecological studies. The chapter illustrates the value of HyFFlow for providing this information; while it is applied here to the Baleh, it is considered a generic approach applicable to any river.

3.2. HyFFlow framework and Work Packages

3.2.1. Overview

HyFFlow is based on analysis of existing discharge and rainfall data. Thus, as with all approaches to characterisation (e.g. Indicators of Hydrological Alteration), confidence in conclusions drawn from the various analyses that make up HyFFlow depend on the duration of the data record. Ideally, long data time series (decadal) of hourly or daily values are available. Depending on data availability, it may be inappropriate to apply some of the analyses.

HyFFlow provides a way to understand flow characteristics over several timescales: (i) the event scale, based on the traits of individual events, (ii) seasonal scale, and (iii) annual and interannual scales. Flow variability over these timescales is known to influence ecological, geomorphic and bio-geochemical processes in riverine systems (Yarnell et al., 2015) and so maintaining natural patterns of this variability is important for maintaining river integrity when flows are altered or modified. A specific focus of HyFFlow is the statistical identification and characterisation of different 'types' of hydrological event, and assessment of their frequency and timing.

The framework is divided into 4 packages (Fig. 3.1), each consisting of a number of analyses designed to yield information on different aspects of the flow regime. The following sections provide details of the rationale and analyses that form respective packages. These are followed by an example to show how it has been applied to the Baleh River (Fig. 3.2). The main part of the Fig. 3.2 shows the catchment upstream of the confluence of the Baleh with the mainstem Rajang. As shown in Fig. 3.2(a)-(g), rainfall data are missing for some of the early years of the period of flow records. Of those stations in the Baleh, Nanga Entawau has the longest and most complete data, though a slightly more complete record exists for Nanga Merit which sits in the main Rajang catchment. Application of the framework leads to the production of a large number of plots and data tables. For brevity, only a small number of these are presented here; the remainder are given in the Appendix Section.

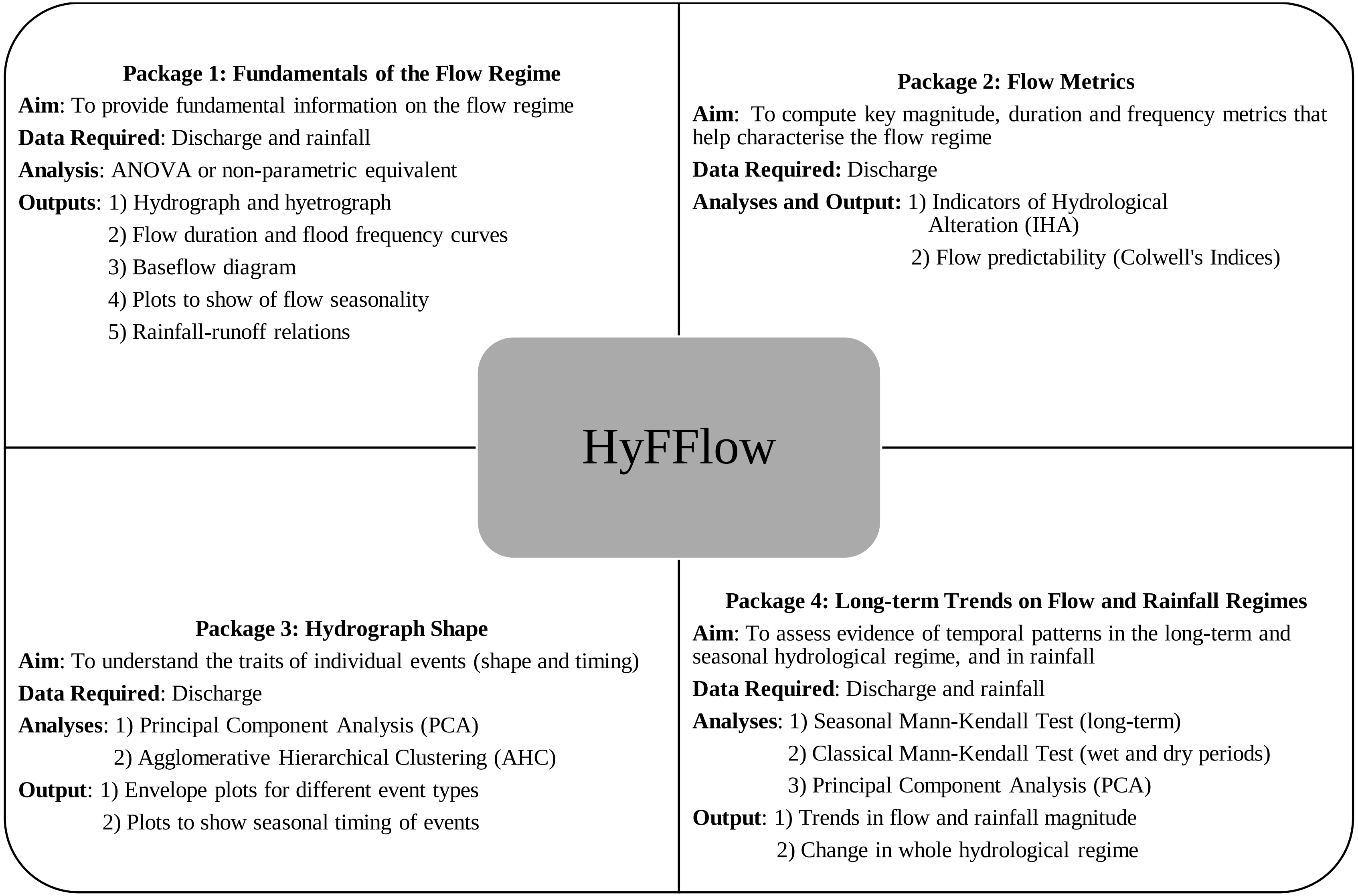

Figure 3.1 Schematic of the flow regime analytical framework.

Package 1. Fundamentals of the flow regime

Package 1 provides fundamental information on the river flow regime, as well as the links between rainfall and flow magnitude. This package is largely descriptive, with most of the outputs being plots designed to represent fundamental information on the regime. They include basic time series plots, flow duration curves, flood frequency plots, and assessment of the magnitude of and seasonal variation in baseflow. Baseflows are calculated using BFI+ 3.0 module of HydroOffice© 2010 software, which uses the local minimum method (Gregor, 2010). The analysis of rainfall includes some formal statistical tests to assess rainfall-runoff relationships and, when data for multiple stations are available, tests to assess variation in rainfall and rainfall-runoff relations.

Package 2. Flow metrics

This package uses a variety of metrics to represent key aspects of the regime quantitatively. It uses the Indicators of Hydrological Alteration (IHA) software developed by The Nature Conservancy (TNC, 2007) to compute a range of flow metrics. These metrics are based on work by Poff and Ward (1989). The metrics capture aspects of the flow regime's magnitude, as well as the timing and duration of certain flow events.

Application of the IHA software yields a simple table of metric values that identify key aspects of the regime. For example, Q_{90} (90th percentile) is used in IHA to define 'low flow', and Q_{95} (95th percentile) to define 'extreme low flow'. IHA also provides a simple classification of high flow events, based on standard flow percentiles and recurrence intervals. What are termed 'high flows' are events whose magnitude exceeds 75% of all daily flow values in the record; the 'small flood' threshold is the 2-year recurrence interval, while 'large floods' have a 10-year recurrence interval. The IHA statistics are a useful way of describing a river's flow regime in ways that have been shown to be ecological relevant (Richter et al., 1996). For instance, extreme low flows (e.g. flows equalled or exceeded 95% of the time, Q_{95}) enable recruitment of certain floodplain species and may concentrate prey into limited areas to benefit predators (The Nature Conservancy, 2009). Such flows will expose sediment on gravel and sand bars, habitat that is important for many rare species (Sadler et al., 2004). Conversely, the magnitude and timing of high flows can be important as such events can act as disturbances that influence community structure (Gibbins et al., 2001) or the timing of life-cycle events (Lytle and Poff, 2004). Overbank flows are recognised FF components that support a broad suite of physical and ecological processes, including the maintenance of habitat heterogeneity in space and time, controlling patterns of riparian succession, and providing cues for fish reproduction and migration (Yarnell et al., 2020). For HyFFlow, statistics representing high and low flow magnitude, timing and duration form the starting point for a more sophisticated analysis of hydrograph shape undertaken as part of Package 3.

The final analysis included in Package 2 involves computing Colwell's Index (Colwell, 1974). This quantifies the predictability of a flow regime and is particularly useful within the context of seasonality – e.g. highly seasonal regimes, such as found in Mediterranean regions, may be highly predictable. Predictability (P) has two separable components - constancy (C) and contingency (M), which have profoundly different implications for the ecology and evolution of biological systems (Fretwell, 1972; MacArthur, 1972; Colwell, 1974). Maximum predictability can be attained as a consequence of either complete constancy, complete contingency, or a combination of constancy and contingency with respect to time (Colwell, 1974). When used in the analysis of streamflow, C is a measure of the degree to which streamflow is the same (constant) and M is a measure of the degree to which the annual pattern of flow repeats (Milhous, 2012). These elements of predictability can be compared to other rivers. Colwell's index can be computed using the R package 'hydrostats' (R Core Team, 2013).

Package 3. Hydrograph shape

Larger events serve important geomorphic functions by initiating sediment transport and topographic change in river reaches (Church, 2002), and may also be ecologically important (Benda et al., 2004; Death et al., 2015). The focus of Package 3 is the statistical identification and characterisation of these larger events. Potentially important event traits are their peak magnitude, duration and rates of change on the rising and falling limbs, as well as their timing. Package 3 involves identifying all events within the IHA high flow event classes (i.e. 'High Flows', 'Small Floods' and 'Large Floods') over the data period, and then using a sample of these for a full analysis of their traits. Depending on the user and focal river, additional high flow classes may be delineated and included in the analysis. For example, flows of a lower magnitude than IHA-defined 'high flows' may still serve important geomorphic or ecological functions, so such events may need to be included. Similarly, it may not be operationally possible to create managed flows from dams at the magnitude of the default three IHA High Flow classes, so additional smaller classes may be developed to ensure inclusion of events small enough to be released from the dam. For instance, in the case of the Baleh, a fourth class was created to allow inclusion of events greater than the median flow but less than the IHA 'High Flow' threshold (see Section 3.3.2).

Package 3 requires a large enough number of events across all classes to allow meaningful analysis of their traits. A minimum sample size of approximately 100 events is suggested for this. In the Baleh for example, there was a total of 1949 events within the four high flow classes over the 51-year data period. A stratified random method was used to select a sample of events from this total, designed to yield a percent (%) frequency of events of each class in the sample that matched that in the full data record. Events chosen to represent each class were selected randomly from all events belonging to that class. Fig. A1 (Appendix 1) shows the breakdown of the sample by event class for the Baleh.

The analysis of the event shapes uses multivariate methods proposed by Hannah et al. (2000) and Fong et al. (2016). These methods involve characterising each event using the discharge values from their start to end points; thus, shape is defined using the discharge time series that captures their rising limb, peak, time at peak, falling limb and duration. Ideally, hourly discharge data are used for this analysis but in some cases only mean daily values may be available. Availability of only mean daily values creates some problems for analysis of shorter events (e.g. events of just one or two days duration cannot be analysed meaningfully in this way). Careful judgement is needed about inclusion of shorter events when mean daily values are used. For example, in the case of the Baleh, events less than 5 days were excluded from the multivariate analyses and characterised differently (further details below).

The analysis of shape has three stages. First, for each sample event, discharge magnitude for each time interval over its duration is used as the input for an Agglomerative Hierarchical Clustering (AHC). This clustering identifies events of similar shape objectively, with these clusters becoming the 'event types'. Second, simple envelope plots of each type identified by the AHC are then produced. To produce these plots, hydrographs for all events within a given type are plotted together, with non-linear Generalised Additive Models (GAMs) fitted to the upper and lower bounds (10th and 90th quantiles) to create a smoothed curve that defines the limits of each type. So as to not 'loose' any short events omitted from the clustering, these are plotted together in an additional diagram, with GAMs then fitted to model upper and lower bounds of the scatter on this diagram. GAMs can be fitted in the 'mgcv' package within R (Wood, 2011), or a number of other software packages.

Finally, following Hannah et al. (2000) and Fong et al. (2016), Principal Components Analysis (PCA) is applied to the same data and format used for the AHC (i.e. discharge at each time interval over the duration of each event). From this PCA, factor loadings on the most useful PCA components (highest explanatory power) are plotted to provide a complementary insight into event shape; this allows assessment of the key ways in which event types differ.

Package 4. Long-term trends in flow and rainfall regimes

This package is focussed on looking for evidence of any changes in rainfall and hydrological regime. It provides an objective analysis of inter-annual and long-term trends. The package produces 2 main outputs: (a) assessment of trends in flow and rainfall magnitude and frequency, (b) assessment of change in the whole hydrological regime. Discharge and rainfall data are required (daily or monthly).

(a) uses standard statistical tools (Mann-Kendall test) to look for evidence of linear and monotonical trends in flow and rainfall at monthly and seasonal scales. Seasonal Mann-Kendall test allows for time series within which there may be seasonal rhythms nested within any longer-term directional (linear) change. This test is applied to monthly discharge and rainfall values over the available time series. Standard Mann-Kendall tests are also applied for seasons of interest. These seasons depend on location; for instance, in the case of the Baleh, they were defined using wet and dry periods connected to the monsoon and so the analyses assessed long-term changes in mean discharge for the wet and dry seasons.

(b) uses PCA to characterise and compare the regime of each year. Each year is characterised using a variety of flow metrics, with the PCA of these metric values allowing assessment of the similarity of each year as well as the identification of the most useful metric(s) for such comparisons (termed ‘key metrics,’ as they are the features of the regime that vary most between the years). GAMs are then used to look for evidence of long-term trends in (i) the annual values of each key metric, and (ii) the annual regime overall (using PCA component 1 scores for each year).

Standard metrics that represent various aspects of flow magnitude, frequency, duration, timing, variability, and rate of change are used for (b). A large number of potential metrics exist (e.g. see Olden and Poff, 2003), so a subset of these can be chosen to reflect the particular purpose or focus of the study. Once metrics are chosen and computed, an initial PCA is used to identify and remove redundant and correlated metrics. The PCA is then re-run with the remaining subset of metrics. For instance, in the case of the Baleh, 17 of the initial 26 metrics were used in the final PCA. AHC is then used to identify groups of years with similar regimes, with these groups then differentiated on the final PCA. The GAMs fitted to the PCA component 1 scores for each year (e.g. in the case of the Baleh, 51 years) pick out evidence of rhythms, cycles or linear trends in the annual regime. GAMs are also applied to the annual values of the key metrics (metrics with the longest vectors on the PCA); these GAMs provide insights into whether values of any of the metrics (e.g. Q_{90}) are changing over time. The degrees of freedom (edf) in the GAMs were allowed to vary, to allow the models to find the best shape to represent any temporal pattern over the data period.

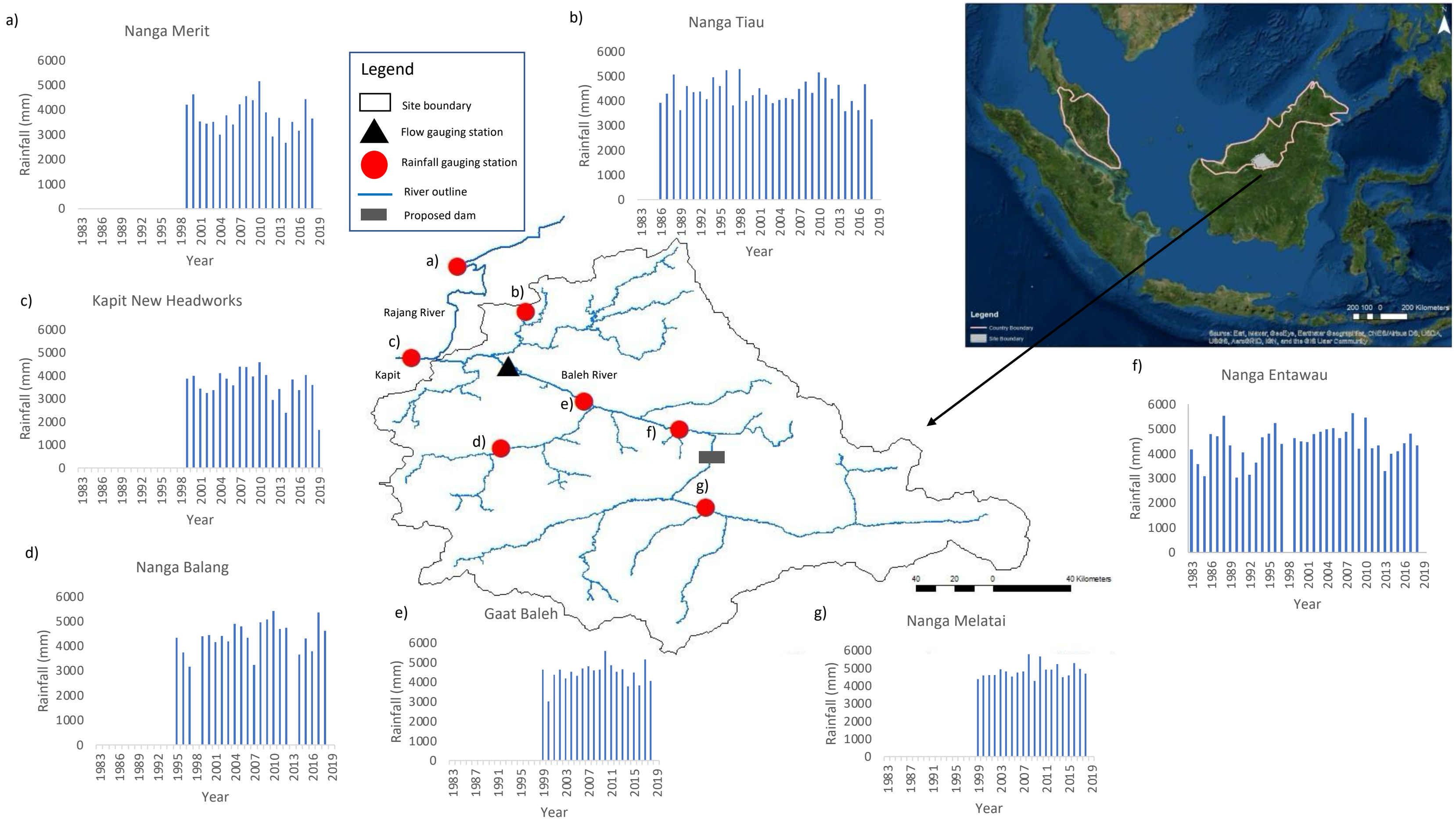

Figure 3.2 Location map of the Baleh catchment, with Telok Buing gauging station (triangle) and 7 rainfall stations shown. Hyetographs showing annual total rainfall for each rainfall station are shown in the map to illustrate the data periods. In the inset map, the Malaysian national border is shown by the pink lines, while the Baleh catchment is shaded grey (Source: Esri, Maxar, Geo Eye, Earthstar Geographics, CNES/Airbus Ds, USDA, USGS, AeroGRID, IGN and the GIS User community).

3.3. HyFFlow Application to the Baleh River

3.3.1. The Baleh Catchment

The Baleh (Fig. 3.2) is one of two main sub-catchments within the Rajang basin and has a catchment area of 5,625 km^2. The Rajang basin is approximately 50,000 km^2, with elevations exceeding 2000 m asl. Floodplains, when present, are of limited area (Staub and Gastaldo, 2000). Geology consists of sandstone and shale from the Belaga and Nyalau Formations (Ling et al., 2016). Soils are mainly Red Yellow Podzols, based on the Sarawak classification system (Tie, 1982). Landcover in the Baleh catchment is predominantly hill forest, comprising mixed dipterocarp and secondary forest. Annual total rainfall is among the highest in Sarawak, exceeding 5000 mm in most years. There is usually an average of around 250 days of measurable precipitation per year. Temperature is high throughout the year, with a mean annual daily maximum temperature of 33 ºC.

Flow data from the Telok Buing gauging station obtained from the Department of Irrigation and Drainage (DID) Malaysia are used to illustrate HyFFlow. The data record commences in 1967 and extends until 2017. To complement discharge data, seven weather stations provide information on rainfall, though for varying periods and durations. The locations of gauging and weather stations, along with respective data, are shown in Fig. 3.2.

3.3.2. HyFFlow Outputs

In this section, some of the key outputs from each package are presented and these are used to illustrate the characteristics, patterns, and trends evident in the flow and rainfall data for the Baleh. These findings are discussed within the context of climate and landcover change, as well as the operation of Baleh Dam, in Section 3.4.

Package 1

Fig. A2 (Appendix 2) shows the basic discharge data for Telok Buing, along with rainfall for the closest upstream weather station (Nanga Entawau). Figs. 3.3–3.5 and Figs. A3–A5 give the HyFFlow outputs used to represent the fundamental aspects of the flow regime, while Fig. A6 shows rainfall-runoff relations.

Degree of Seasonality

Plots of median monthly discharge and rainfall data (Figs. 3.3 and A3) show that the Baleh has a monsoonal tropical regime rather than a seasonal tropical one, with the wet months being November to March, and dry months May to August. The strength of seasonality is quantified further in Package 2 using Colwell's index (for which see below). Baseflows vary considerably in the Baleh (Figs. 3.4 and A4), but typically are less than 500 m^3/s in the dry months, and 500 − 800 m^3/s in wet months.

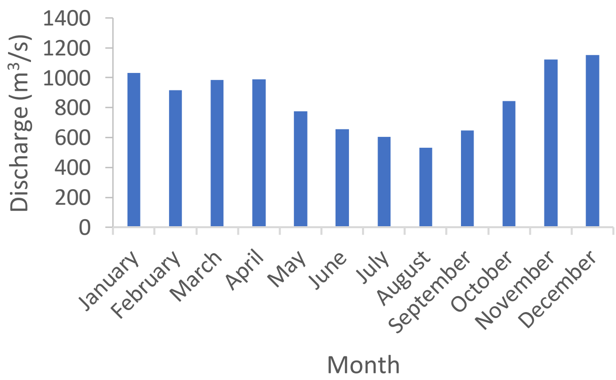

Figure 3.3 Median monthly discharges in the Baleh (1967-2017).

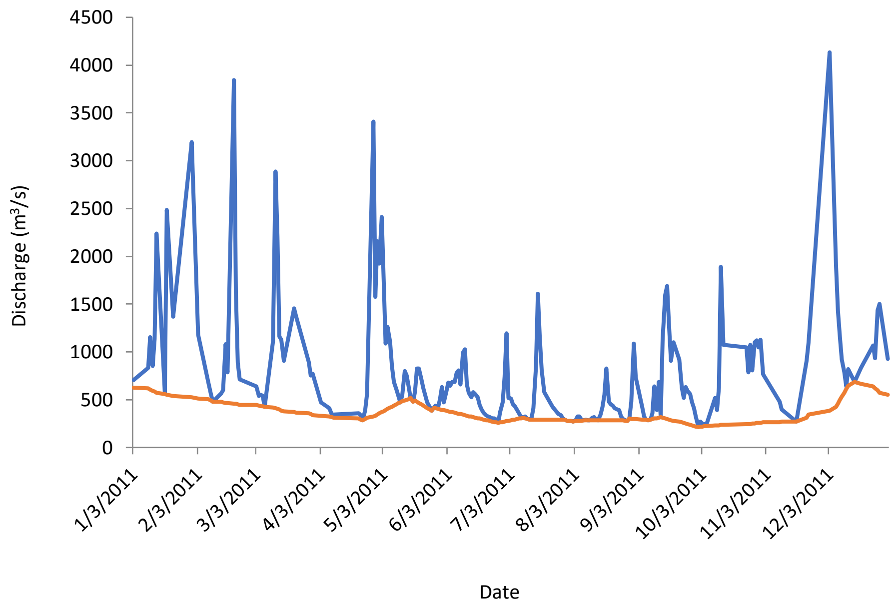

Figure 3.4 Example of an annual hydrograph for the Baleh, showing daily discharge magnitude and baseflows.

Flow Duration and Flood Frequency Curves

Flow duration curves for each year of record are shown in Fig. 3.5(a), with the inset showing the long-term values. Each year is plotted to help visualise interannual variation in the flow regime. The long-term median flow for the Baleh is 873 m^3/s, with a 90th percentile of 376 m^3/s, and a 10th percentile of 1915 m^3/s. There is, however, significant variability in the annual flow duration curves, with e.g. Q_{50} varying from around 900 m^3/s to 2000 m^3/s. For the period of record, 1970 and 2014 represent extreme high and low flow years respectively.

The flow value corresponding to a 5-year return period event for Baleh River is approximately 4200 m^3/s (with the exceedance probability being 20%), with a 10-year return period event being equal to approximately 5000 m^3/s (with the exceedance probability being 10%) (Fig. 3.5(b)).

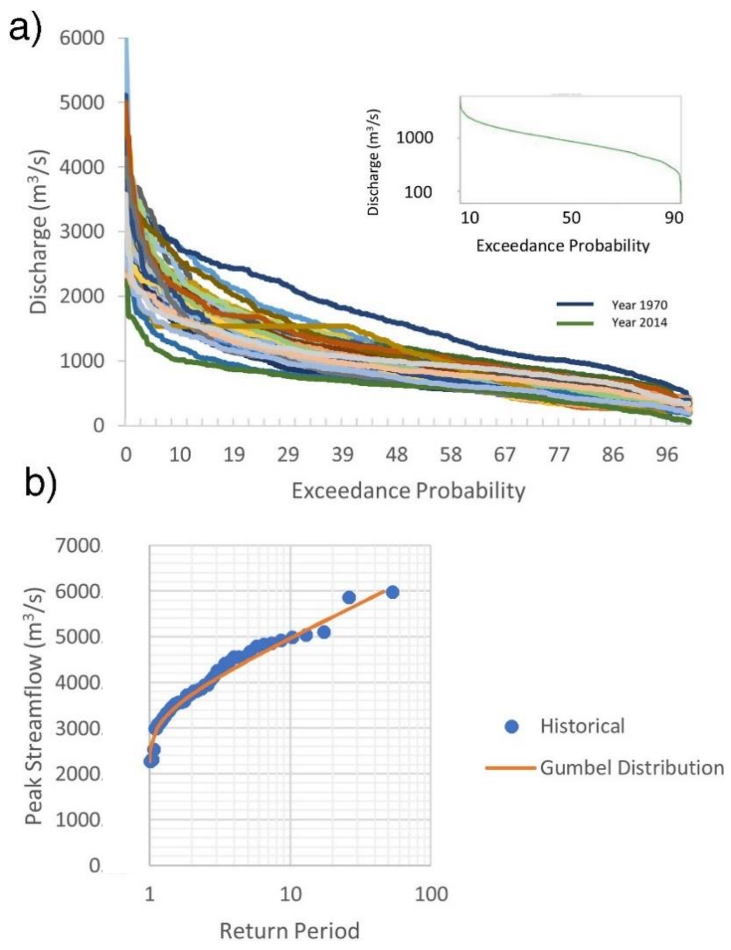

Figure 3.5 Flow and flood-frequency plots for the Baleh River. (a) Flow duration curves for all 51 years (1967-2017 data). The inset shows the long-term flow duration curve. Note that the curves for 1970 and 2014 represent the upper and lower limits of the envelope defined by all the flow duration curves. (b) Flood frequency curve plotted using Gumbel Distribution.

Rainfall-runoff Relations

Rainfall in the Baleh varies significantly between the weather stations included in the analysis (ANOVA: df 6, 2476; F 13.773; $p < 0.05$). Results from post-hoc tests show that Nanga Merit and Kapit New Headworks sites differ from the other five locations, but the others do not differ from each other (Fig. A5). These two drier stations are the most westerly ones, and both sit just outside the Baleh sub-catchment but within the Rajang (Fig. 3.2). Rainfall-runoff plots indicate similar relations between discharge at Telok Buing and precipitation at various points in the catchment (Table 3.1 and Fig.

A6). Thus, there is no evidence that rainfall magnitude in different parts of the catchment produces a different response in discharge at Telok Buing.

Table 3.1 Equation and the R-squared values for regressions of discharge at Telok Buing and the 4 upstream rainfall stations (see Fig. 3.2 for location details). In the equation, the Y-axis represents monthly discharge (m^3/s), and the X-value represents mean daily rainfall per month (mm).

Rainfall Station	Data Period	Data Points (N)	Linear Equation	R^2	p-value
Nanga Entawau	Oct 1970-2017	420	y = 46.418x + 395.97	0.39	2.283E-47
Gaat Baleh	June 1998-2017	232	y = 49.981x + 334.86	0.44	1.420E-30
Nanga Balang	1995-2017	256	y = 47.731x + 380.65	0.38	8.480E-28
Nanga Melatai	Sept 1998-2017	232	y = 47.403x + 327.96	0.42	9.075E-29

Package 2

IHA Metrics

Table 3.2 shows a subset of the IHA flow metric values for the Baleh. This subset includes the timing of the two low flow percentiles, defined using the days that respective lowest flow events occur on (e.g. the day that the lowest flow event below Q_{95} occurred on). These flows are on Julian day 216 (August) and 212 (July), both of which are in the dry part of the year. However, it is evident from the hydrograph (Fig. 3.4) that flows drop below Q_{95} and Q_{90} throughout the year, and from both the hydrograph and Table 3.2 that such periods are short lived (i.e. only 2–3 days in duration). In general, the river is rain-driven and does not experience extended periods at low or baseflow at a particular time of the year.

Table 3.2 Selected IHA metric values for the Baleh River.

EFC Parameters	Value	Variability (CV)
Annual CV	0.64	NA
Extreme low peak (Q, m^3/s)	251.8	0.1293
Extreme low duration (days)	2	1.25
Extreme low timing (Julian day)	216	0.167
Extreme low freq. (mean/year)	3	2.333
Low peak (Q, m^3/s)	318.4	0.1949
Low duration (days)	2.5	0.85
Low timing (Julian day)	212	0.1691
Low freq. (mean/year)	8	1
High flow peak (Q, m^3/s)	1822	0.1362
High flow duration (days)	2	0.5
High flow timing (Julian day)	317	0.4208
High flow frequency (mean/year)	23	0.3478
High flow rise rate (Q/day, $m^3/s/day$)	467.6	0.3775
High flow fall rate (Q/day, $m^3/s/day$)	-408.6	-0.3259
Small Flood peak (Q, m^3/s)	4081	0.1509
Small Flood duration (days)	10	1.4
Small Flood timing (Julian day)	269	0.4399
Small flood freq. (mean/year)	0	0
Small Flood rise rate (Q/day, $m^3/s/day$)	688.3	0.9428
Small Flood fall rate (Q/day, $m^3/s/day$)	-604.2	-0.9187
Large flood peak (Q, m^3/s)	5109	0.1764
Large flood duration (days)	13	0.5385
Large flood timing (Julian day)	310	0.1967
Large flood freq. (mean/year)	0	0
Large flood rise rate (Q/day, $m^3/s/day$)	646.8	0.4972
Large flood fall rate (Q/day, $m^3/s/day$)	-957.6	-0.5694
% of floods in 60-day period (maximum proportion of floods that occur during any 60 day period)	0.21	NA

Colwell's Index

Fig. 3.6 shows the predictability of the Baleh flow regime relative to other rivers. The Baleh has an overall predictability of P = 0.5, similar to the other tropical monsoonal river included in the plot (Lower Mekong (P = 0.32)). The other tropical rivers in the plot are seasonal ones, while the remainder are temperate rivers. The Baleh predictability is in upper quartile of the tropical rivers but is dominated by constancy (i.e. it has very low contingency). This shows that the Baleh has a greater degree of similar streamflow (C) and lower degree of repeated annual pattern (M). Note that only a few calculations of Predictability have been published for Mediterranean rivers (average P is 0.55), and none of these papers reported the two elements separately.

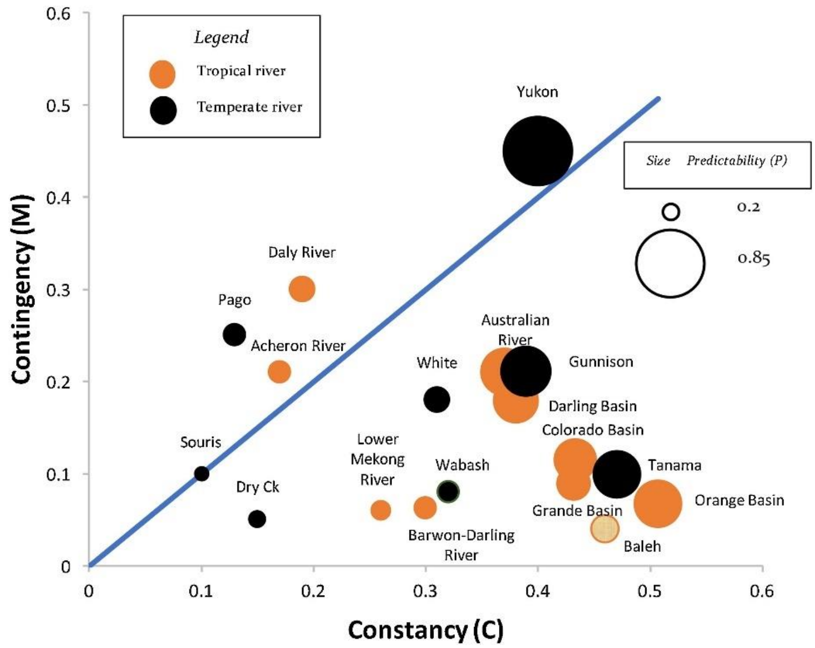

Figure 3.6 Flow predictability of the different types of rivers around the world; the Baleh shaded in light orange. Size of the circles represent predictability (i.e. the bigger the circle, the higher the predictability); the 1:1 line indicated where predictability consists of 0.5 constancy and 0.5 contingency. Published values are taken from Thoms and Sheldon, (2000); Gordon et al., (2004); Moliere et al., (2007); Kennard et al., (2010); Milhous, (2012); Fernandez and Sayama, (2015); Oueslati et al., (2015).

Package 3

Event Types and Their Shapes

The AHC (Fig. A7) of the 86 individual events analysed generated 5 high flow event types, consisting of 3 main groups and 2 single events that did not fit within the main groups. These event types are also shown in the PCA (Fig. A8). The envelope plots (Fig. 3.7) of these event types help illustrate key differences in respective magnitudes, durations and rates of change. Type A represents events that rise sharply, peaking at around 7–9 days at between 100−900 m^3/s (above respective time baseflow levels), and lasting for around 20 days. Type B represents very similar events to Type A in terms of duration, but which have higher peaks (up to around 2500 m^3/s above baseflow) that rise and fall more rapidly. Type C events are rather similar in magnitude to Type B, but are longer (up to 30 days) and more pointed than the dome-shape that characterises Type B. The single events shown in Fig. 3.7(d)-(e) do not fit the other classes because of their complex shape – Event D has a double peak, while E rises sharply but takes some time to return to baseflow. The short events (<5 days) not included in the formal AHC and PCA analyses are also shown as an envelope plot in the Fig. 3.7(f). These short events vary in magnitude, from less than 100 to 500 m^3/s above baseflow and can be considered as being a set of low magnitude, short-lived events.

Most (68 %) of the variability in the sampled Baleh hydrographs could be represented on the first four components of the PCA. Fig. 3.7(g)-(j) shows the factor loadings for these four components, with values on each day (D) indicating the main ways that events differ. F1 (Fig. 3.7 (g)) is the major gradient in the data/PCA. The maximum loading on F1 is from D19-D24. This means that the main way in which events differ is in their magnitude at Days 19–24. In effect, while some events are still going on beyond 19–24 days, by this time others have ended and have dropped back to baseflow; thus, the primary division of events separates those shorter than, and those longer than 19–24 days. This division is evident from the envelope plots (Fig. 3.7(a)-(f)): Fig. 3.7(b) shows event types shorter than 19–24 days while Fig. 3.7(c)-(e) show those longer than this.

Maximum loading on F2 (the next most important dimension) is around Day 9. This separates events according to their flow discharge on Day 9–11, and clearly helps separate event types (a) and (b) in Fig. 3.7, with (a) having a lower discharge on this day.

Fig. 3.8 shows seasonal patterns in the occurrence of events belonging to each of the four event types described above (the two single events are omitted). Event Types A and F show the clearest seasonal patterns. Type A is bimodal, with peaks of occurrence in Weeks 21–25 (late May to early June) and then 47–52 (November and December), while Type F occurs most frequently during Weeks 22–31 (late May to late June). The other types have more variable, less clear seasonal patterns, though Type B events tend to occur more commonly towards the end of the year. Type C (the higher magnitude events) occur mainly in the final third of the year (Week 31 onwards), and much less commonly in the dry months of May to September (Weeks 19–40).

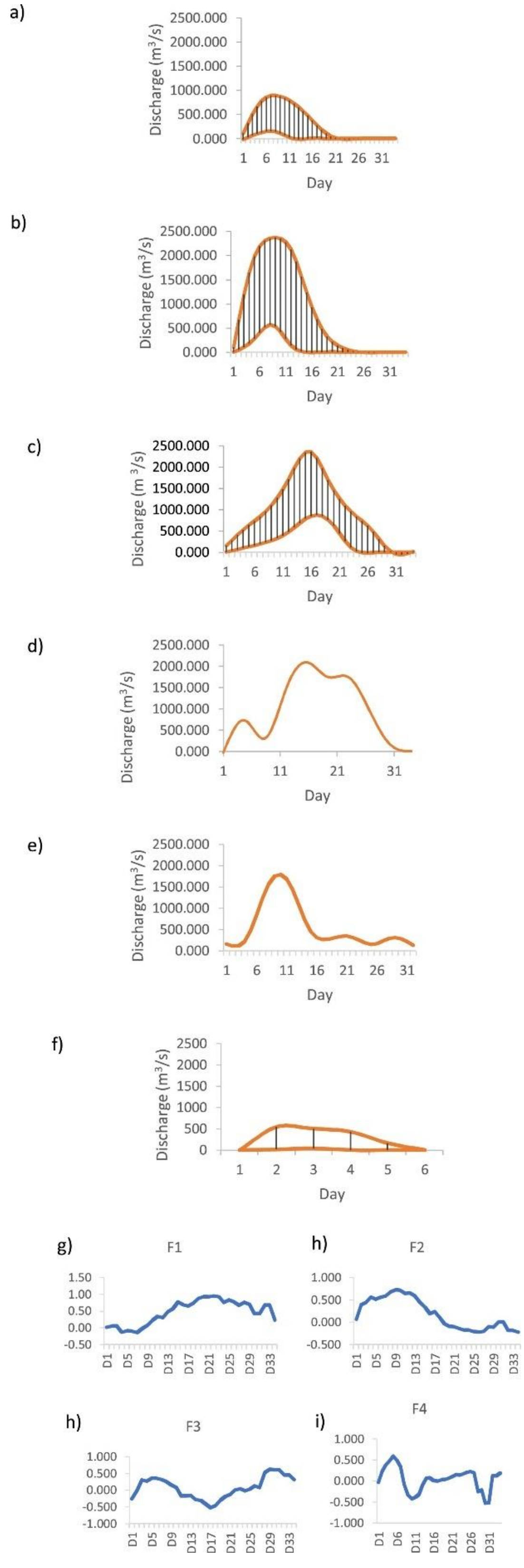

Figure 3.7 Traits of high flow events. (a)–(c) Envelope pots of event Types A–C identified from the PCA and AHC, along with the two individual events that did not fit these main types, shown in (d)-(e), which are events numbered 48 and 62 respectively in Fig. A8. (f) Envelope plot of

events less than 5 days in duration. Envelopes plot the 10th and 90th percentiles for all events within each group, with lines modelled using GAMs. Note that events are shown not as absolute discharge but increase above baseflow. (g)–(j) show the shapes of the first 4 component loadings from the PCA.

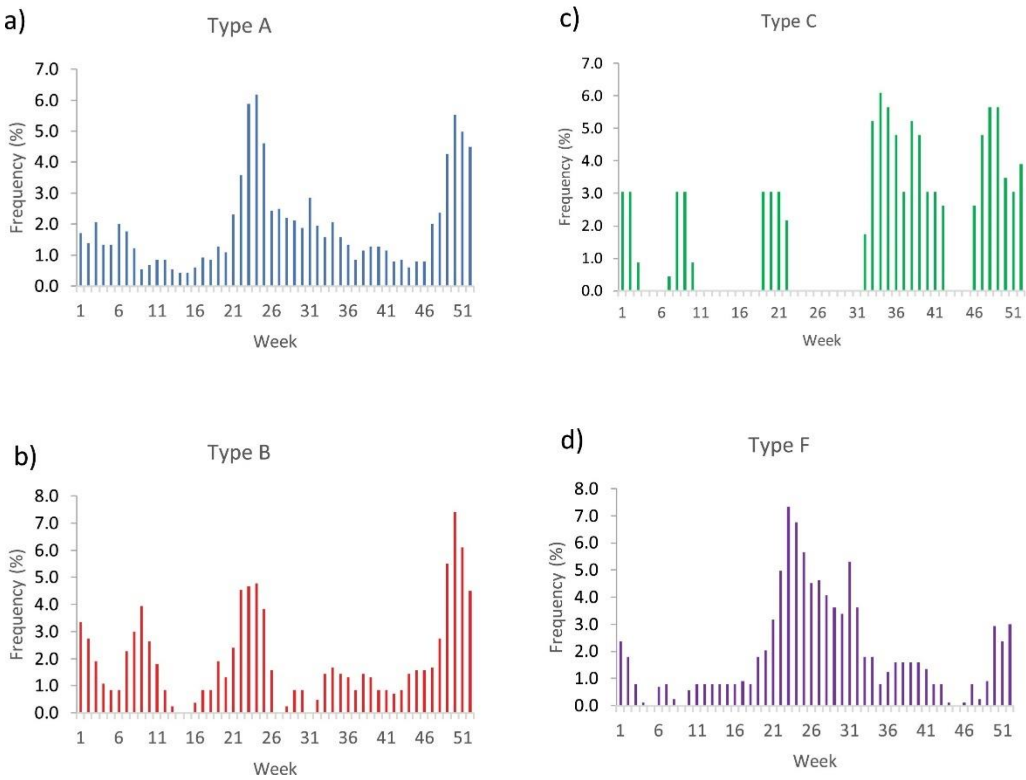

Figure 3.8 Timing of high flow event types in the Baleh River.

Package 4

Trends in Rainfall and Flow

There were no significant trends in monthly mean or maximum monthly rainfall at any of the 7 rainfall stations (Tables 3.3 and 3.4). Hence, there was no evidence of gross long-term changes in rainfall magnitude across the catchment as a whole. At the seasonal level, there were no significant trends in rainfall in either the wet or dry periods at any of the weather stations. More recent rainfall data were available for Nanga Entawau, but analysis of data for this station indicated that there was also no evidence of any change over the longer period (1970−2019; $p = 0.455$). Nevertheless, a change in rainfall frequency was evident, though this varied spatially across the Baleh: for the 4 stations located in the west of the catchment, there was a decrease in the number of days each month with no rainfall, whereas for the easterly Nanga Entawau station there was an increase in the number of no-rainfall days (Table 3.4).

There was a significant decrease ($p < 0.05$) in discharge in the Baleh over the 51-year period (Fig. A9). However, this varied seasonally, with a significant decrease evident in the wet months but not the dry months (Fig. A10).

Table 3.3 Results of the long-term and seasonal trend test for each of the 7 rainfall stations in the Baleh. Note the different time periods for these tests, as a function of data availability.

		Long-Term			Seasonal			
Rainfall Station	**Year**	**Kendall's tau**	**p-value**	**Sen's slope**	**Season**	**Kendall's tau**	**p-value**	**Sen's slope**
Nanga Entawau	Oct 1970-2017	-0.021	0.539	-0.008	Dry	-0.011	0.897	0
					Wet	-0.05	0.551	0
	Oct 1970-2019	-0.025	0.455	-0.016	Dry	-0.049	0.542	0
					Wet	-0.051	0.531	0
Nanga Tiau	Mar 1986-2017	-0.054	0.143	-0.04				
Kapit New Headworks	Aug 1986-2017	-0.009	0.807	0	Dry	-0.055	0.529	0
					Wet	0.071	0.429	0
Nanga Balang	1995-2017	0.022	0.628	-0.048	Dry	-0.108	0.307	0
					Wet	-0.044	0.694	0
Nanga Melatai	Sept 1998-2017	0.046	0.347	0.085				
Gaat Baleh	June 1998-2017	-0.051	0.303	-0.076				
Nanga Merit	1967-2017	0.025	0.383	0.017	Dry	0.037	0.598	0
					Wet	0.09	0.203	0

Table 3.4 Results of the trend test on the extreme rainfall events (i.e. maximum monthly rainfall and number of zero-rainfall days) for each of the 7 rainfall stations. Note the different time periods for these tests, as a function of data availability.

		Maximum monthly rainfall			**Number of zero-rainfall days**		
Rainfall Station	**Year**	**Kendall's Tau**	**p-value**	**Sen's slope**	**Kendall's tau**	**p-value**	**Sen's slope**
Nanga Entawau	Oct 1970-2017	0.025	0.467	0.000	0.093	**0.008**	0.049
	Oct 1970-2019	0.024	0.477	0.107	0.094	**0.006**	0.056
Nanga Tiau	Mar 1986-2017	-0.061	0.092	-0.419	-0.089	**0.017**	-0.023
Kapit New Headworks	Aug 1986-2017	-0.004	0.911	-0.172	-0.16	**<0.0001**	-0.092
Nanga Balang	1995-2017	-0.045	0.328	-0.383	-0.158	**0.001**	-0.111
Nanga Melatai	Sept 1998-2017	0.038	0.437	0.625	-0.066	0.18	0
Gaat Baleh	June 1998-2017	-0.017	0.730	-0.4	0.046	0.354	0
Nanga Merit	1967-2017	-0.008	0.774	-0.041	-0.166	**<0.0001**	-0.078

Change in The Whole Hydrological Regime

Table A1 (Appendix 1) shows the full set of flow metrics produced for analysis of long-term trends in the hydrological regime. These were all computed from the long-term discharge time series for the Baleh, then analysed using AHC and PCA (Fig. 3.9). The three classes of year identified by the AHC are colour coded in Fig. 3.9(a). Class 1 represents years with lower flows, sitting at the negative extreme of several flow magnitude metrics (annual Q_{50}, annual max Q, annual Q_{16} and number of times flow exceeds Q_{16}). Classes 2 and 3 are generally higher flow years; the difference between these related to flow variability – Class 2 is more variable, sitting towards positive end of the vectors for flow CV and SD. The direction of the vectors in Fig. 3.9(b) indicates how the classes differ. Most of the vectors were of similar length, with only those for aspects of timing (TQ > 5, TQ > 16, TQ < 84, TQ < 90) short and hence less important.

PCA factor 1 scores (Fig. 3.10) for each year showed a significant linear trend over time ($p < 0.05$; edf in GAMs of 1; Table 3.5). This shows that there has been a change in the flow regime of the Baleh over the last 51 years; Factor 1 scores have reduced over time, indicating a shift to a ‘lower flow’ regime. This multivariate analysis of the whole regime therefore corroborates the Mann-Kendall test results applied to the raw discharge magnitude data.

Significant trends were evident in the values of YCV and ANMmax (Fig. 3.10 and Table 3.5). The high edf values indicate non-linear cyclical patterns, rather than linear or directional trends. Thus, the models indicate that there were intra-annual differences in terms of flow variability and magnitude, with cycles of wet and dry years. No significant patterns were evident in nQ_{90} or nQ_{50} ($p > 0.05$).

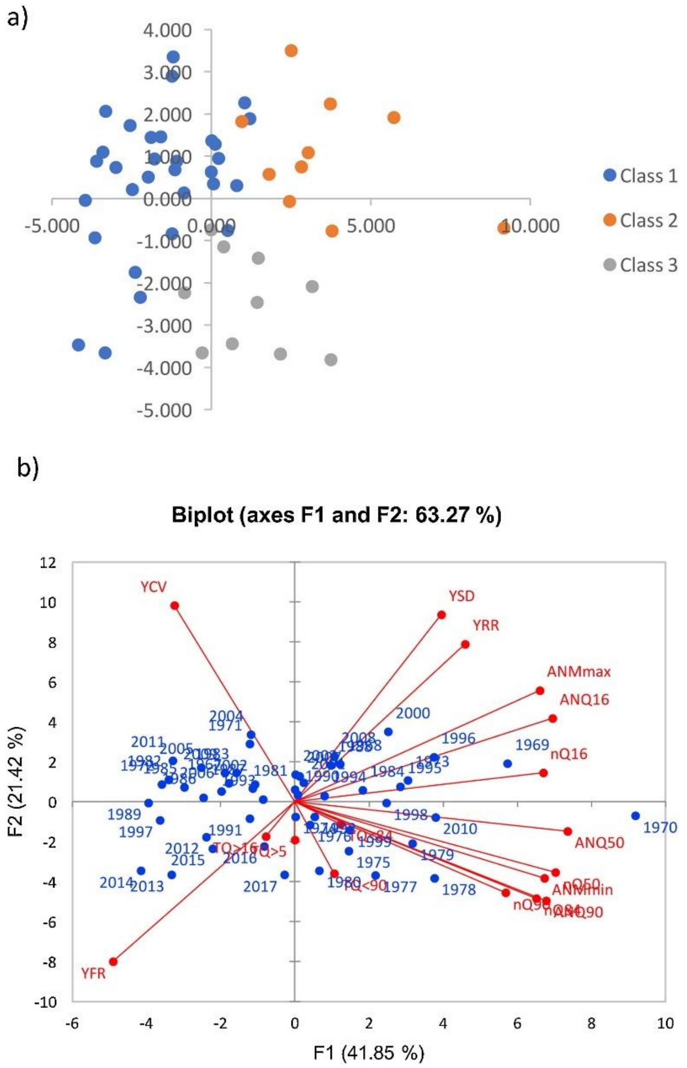

Figure 3.9 PCA output of the long-term flow regime characterised using flow metrics shown in Table A1. For the PCA, each year had a value for each metric, with these values then forming those used the characterise each year in a multivariate way. (a) PCA with years colour-coded according to the AHC cluster analysis. (b) PCA biplot, showing years and length of vectors/metrics.

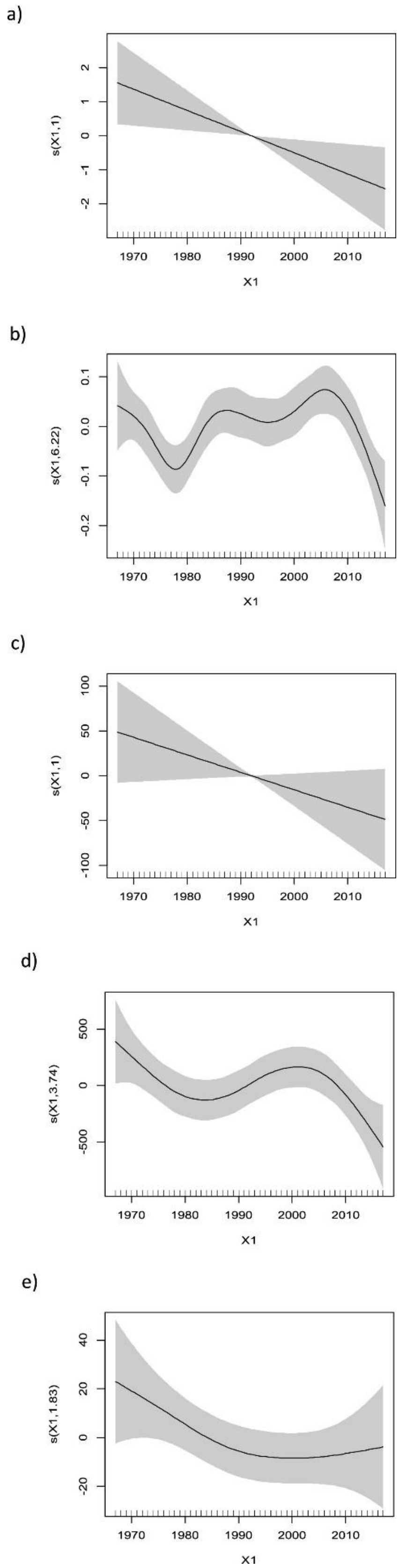

Figure 3.10 Trends in various traits of the long-term hydrological regime of the Baleh River. (a) Factor 1 scores; (b) YCV; (c) ANQ_{90}; (d) ANMmax; (e) nQ_{50}. The shaded areas are the 95% confidence intervals of the fitted smoothers.

Table 3.5 GAM model results for time series analysis of the Baleh hydrological regime.

Flow Metric	edf	Ref.df	F	p-value
Factor 1 Score	1.000	1.000	6.543	**0.014**
YCV*	6.219	7.357	4.270	**0.001**
ANQ_{90}**	1.001	1.002	2.981	0.091
ANMmax***	3.735	4.613	3.329	**0.014**
nQ_{50}****	1.828	2.280	1.794	0.167

* Coefficient of Variation (yearly)

** Annual Q_{90}

*** Mean maximum monthly discharge (annual)

**** Number of times exceeded Q_{50}

3.4. Discussion

3.4.1 HyFFlow: A Systematic Amalgamation of Tools and Metrics

HyFFlow is a framework designed to provide a comprehensive description of the flow regime of a river. It represents a systematic amalgamation of what were previously separate ways of analysing hydrological time series. While developed initially to provide a baseline characterisation of the tropical Baleh River prior to dam construction, HyFFlow can be applied to any river type and can be useful within other contexts (e.g. understanding baseline conditions prior to deforestation). Extracting as much information as possible from existing data may be particularly important in data-scarce regions, such as in tropical countries where human pressures on river systems are great (Jumani et al., 2020). HyFFlow consists of a set of packages that characterise various components of the flow regime, including objective identification of event types whose functional significance either for geomorphic or ecological processes can be investigated as part of targeted follow-up studies. This structured approach to characterisation complements and/or could be used as part of existing holistic frameworks such as ELOHA (Poff et al., 2010). HyFFlow includes an assessment of change. While some existing approaches allow explicitly for this (e.g. Ecodeficit/Ecosurplus concept, Dundee Hydrological Regime Alteration Method, annual proportional flow deviation; Gehrke et al., 1995; Black et al., 2005; Vogel et al., 2007), HyFFlow differs in its approach: it uses a combination of time series analysis to assess trends in flow magnitude, but notably also uses multivariate analyses to assess changes to the 'whole regime' and determine which aspects of the regime have changed.

The potential future development of this tool involves its automation to support data analysts. HyFFlow could be used by hydrologists, hydraulic engineers, ecologists, and biologists, to facilitate data analysis and representation of hydrological conditions and trends. This highly novel automation would mean that by uploading only discharge and rainfall data, practitioners could execute all the analyses and generate the graphical outputs presented in the chapter. We have already opened discussions with computer scientists to begin to develop this into a software tool and currently have a prototype.

3.4.2. Hydrology of the Baleh River

Time-series analyses (Package 4) indicated long-term changes in flow in the Baleh, with reductions in discharge during the wet months of the year. This is broadly consistent with patterns reported by Sa'adi et al. (2017a) who studied a number of catchments across Borneo, including the upper Rajang. The cause(s) of this long-term trend in the Baleh are unclear. There was no change in rainfall magnitude over the same period (though there was some change in rainfall frequency, indicated by increases in the number of days with no rainfall). Of the catchments modelled by Sa'adi et al. (2017b), the Baleh was predicted to experience the least change in rainfall (−1.1 – 1.9% by the end of this century). There has been no major change in landcover in the Baleh, with forest cover being reduced by less than 4% over the last 20 years (Lum, unpublished MRes thesis). Thus, neither rainfall nor landcover change provide a clear explanation for the hydrological change. Sarawak is, however, experiencing an increase in temperature in the range of 0.1–0.15 ◦C/decade (Sa'adi et al., 2017a) and the increase in evapotranspiration associated with this might help explain the long-term reduction in flows in the wet season in the Baleh.

Flows in the Baleh vary considerably over shorter timescales. There is marked inter-annual variability in discharge, with Q_{50} for example varying from 1000 m^3/s to more than 2000 m^3/s between years. The Baleh has a monsoonal tropical climate (rather than a seasonal one), with wet months of November to March and dry months of May to September. Baseflows are somewhat higher in the wet periods (approx. 700 m^3/s) than dry periods (approx. 500 m^3/s). Periods of low flow (Q_{90} and Q_{95}) occur throughout the year and tend to be very short-lived, lasting only (2–3 days).

Four main types of high flow event occur in the Baleh, as well as some idiosyncratic events that do not fit any of these main types. The main types differ in terms of their magnitude and duration. Event Types A and F (respectively, those up to approximately 1000 m^3/s above baseflow and lasting approximately 3 weeks, and those up to 500 m^3/s above baseflow lasting up to five days) have quite consistent patterns of timing during the year. The other two event types are larger (up to 2500 m^3/s above baseflow) and differ mainly in their duration and shape (slope of rising and recession limbs); Type B is around 20 days duration and Type C around 30 days. The long-term data indicate that the timing of these sustained periods of high flow is rather less consistent than Types A and F. Flow predictability (P) of the Baleh, computed using Colwell's index, is moderate and within the range of other tropical rivers. Notably though, it has a low value of contingency, indicating that temporal rhythms are not strong; this reflects the fact that seasonality in the Baleh, while evident to some degree, is not marked, and that both high and low flows occur at any time during the year.

3.4.3. Functional Flows and Dam Operation in the Baleh

The dam currently being constructed on the Baleh is scheduled for completion in 2026. Detailed information on species' flow requirements and life cycles is missing for the Baleh (a common problem in tropical regions), so it is not currently possible to apply habitat models (e.g. PHABSIM; Bovee, 1985) to develop operational regimes based directly on ecological criteria. Similarly, knowledge of fluvial processes in the Baleh is insufficient to identify flows that serve important habitat forming functions and which therefore need to be maintained in order to support geomorphic integrity. The insights into the hydrological regime of the Baleh provided by HyFFlow are therefore important as they provide a clear focus for geomorphic and ecological studies. Most notably, a key task for the Baleh is now to undertake work to understand the functional roles of each of the main event types identified, e.g. how they influence scour, sediment transport and associated changes in habitat (bed sedimentary and topographic conditions).

The HyFFlow outputs showing the timing of occurrence of these events provide a clear template for scheduling dam releases to mimic those events which prove to have important functions. The largest natural events in the Baleh (those greater than 2000 m^3/s; event Types B and C) exceed the combined release capacity of the dam turbines (620 m^3/s) so may be 'lost' post-impoundment unless they are generated by rainfall in the lower parts of the catchment. Event Types A and F, however, could be simulated by artificial releases designed to mimic their shape (as per Fig. 3.7). These two types, unlike the larger ones, have rather clear seasonal patterns of occurrence, so releases could potentially be made to mimic their timing as well as shape.

The HyFFlow analyses also provide some insights into operational rules for managing lower flows. The timing of monsoon periods in the Baleh gives rise to lower mean monthly flows on the months May to August inclusive, with somewhat lower baseflows during these months than the remainder of the year. While the lowest absolute flows also tend to occur during this period, it is evident from the hydrograph (Fig. 3.4) that flows drop below Q_{95} and Q_{90} throughout the year. Such periods tend to be short-lived, with durations of 2–3 days, and the river does not experience extended periods at low or baseflow at any particular time of the year. Thus, sustained periods releasing only compensation flow from the dam, or operating only one turbine (124 m^3/s), would create a very unnatural hydrograph.

One possible constraint on flow management in the Baleh is that the observed long-term trends in flow may impact water storage, and hence the capacity for making FF releases. Even if water is available to deliver a set of designed FFs, providing these in a fixed form (magnitude, shape) may be problematic if geomorphically the river is adjusting to a slow, directional change in flows. Similarly, as landcover change affects runoff and fine sediment loads, such change may alter the geomorphic effectiveness of specific magnitude FF events that were initially designed under different rainfall/runoff relations. Thus, the effects of any FFs would need to be monitored, to ensure they continue to provide the functions intended.

3.5. CONCLUSIONS

River systems globally face multiple pressures, so ways of characterising flow regimes are important for helping to understand these pressures and developing management programmes. Recent research (Hayes et al., 2018) shows that multiple elements of the natural annual hydrograph are necessary to maintain the ecological integrity of riverine ecosystems and their related components (i.e. river channel, riparian areas, floodplain and groundwater). Water management must therefore ensure that all flow regime components (e.g. mean flows, flow pulses, floods) occur in a correctly timed fashion, with the right frequency and duration and rate of change between flow seasons (Yarnell et al., 2015).

HyFFlow provides a comprehensive characterisation of flow regimes and of any changes to these. It does not provide management prescriptions, but rather is a system that allows for characterisation and quantification in ways that are likely relevant to geomorphic processes and ecological integrity. The work presented here for the Baleh is the starting point for post-impoundment flow management designed to maintain physical and ecological integrity. HyFFlow identified distinct flow types and seasonal patterns to their occurrence, with for instance short periods of low flows happening throughout the year and events of moderate size (Types A and F) occurring in the middle and end months of the year. This insight helps set a clear suite of research questions for more focussed, process-based studies that are needed to help design an operational regime for the dam.

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APPENDICES

APPENDIX A1

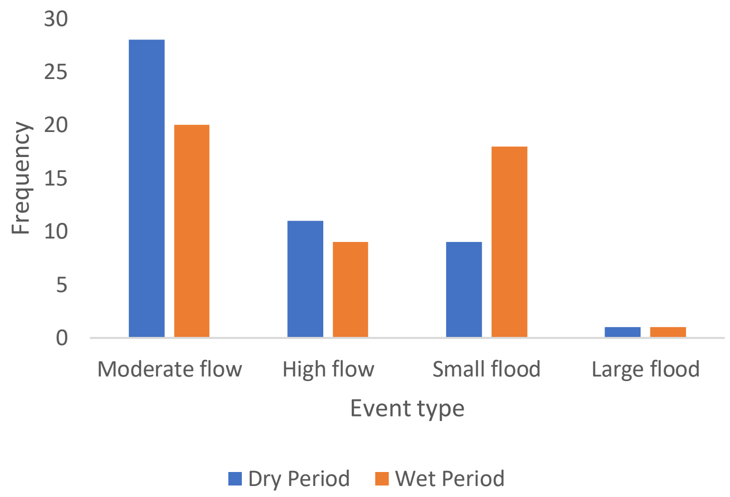

Fig. A1 Breakdown of event types for the Baleh.

Table A1 Flow metrics in terms of magnitude, duration, frequency, variability, timing and rate.

Hydrological Trait Class	Metrics used to represent trait class	Metric definition /Explanation	Metric Code
Magnitude	**Mean annual discharge**	Single long-term value. It is the mean of mean annual discharges for each of the 51 years.	MA
	Mean maximum annual discharge (long-term)	The mean of all the annual max discharges for the 51-year period (this is a single value for the whole data series that we will then use to compare individual years against) (e.g. max discharge in 1967 + max discharge in 1968…/51)	LTMmax
	Mean minimum annual discharge (long-term)	The mean of all the annual min discharges for the 51-year period (this is a single value for the whole data series that we will then use to compare individual years against)	LTMmin
	Mean maximum monthly discharge (annual)	For each year, this is the mean of the max monthly discharges (e.g. max discharge in January 1967 + max discharge in February 1967…/12 months). Thus, we will have 51 mean max monthly discharges.	ANMmax
	Mean minimum monthly discharge (annual)	For each year, this is the mean of the min monthly discharges (e.g. max discharge in January 1967 + max discharge in February 1967…/12 months). Thus, we will have 51 mean max monthly discharges.	ANMmin
	Mean daily discharge for each month	Each month gets a value which is the mean of its daily Qs. We therefore have a value for each month, for each of the 51 years. (e.g. mean discharge for January 1967 + mean discharge for January 1968…/46januaries)	MD
Duration	**Long-term Q_5**	Q_5 calculated from the flow duration curve produced for all 51 years together.	LTQ_5

	Long-term Q_{16}	Q_{16} calculated from the flow duration curve produced for all 51 years together.	LTQ_{16}
	Long-term Q_{50}	Q_{50} calculated from the flow duration curve produced for all 51 years together.	LTQ_{50}
	Long-term Q_{84}	Q_{84} calculated from the flow duration curve produced for all 51 years together.	LTQ_{84}
	Long-term Q_{90}	Q_{90} calculated from the flow duration curve produced for all 51 years together.	LTQ_{90}
	Annual Q_5	The Q_5 value of each year (i.e. 51 values)	ANQ_5
	Annual Q_{16}	The Q_{16} value of each year (i.e. 51 values)	ANQ_{16}
	Annual Q_{50}	The Q_{50} value of each year (i.e. 51 values)	ANQ_{50}
	Annual Q_{84}	The Q_{84} value of each year (i.e. 51 values)	ANQ_{84}
	Annual Q_{90}	The Q_{90} value for each year (i.e. 51 values)	ANQ_{90}
	Monthly Q_5	The Q_5 value of each month (i.e. 12 values)	MQ_5
	Monthly Q_{16}	The Q_{16} value of each month (i.e. 12 values)	MQ_{16}
	Monthly Q_{50}	The Q_{50} value of each month (i.e. 12 values)	MQ_{50}
	Monthly Q_{84}	The Q_{84} value of each month (i.e. 12 values)	MQ_{84}
	Monthly Q_{90}	The Q_{90} value of each month (i.e. 12 values)	MQ_{90}
Frequency	**LTQ_5-AQ_5**	For each year, the difference between that year's Q_5 and the long-term Q_5	Empty Cell
	LTQ_{16}-AQ1$_6$	For each year, the difference between that year's Q_{16} and the long-term Q_{16}	
	LTQ_{50}-AQ_{50}	For each year, the difference between that year's Q_{50} and the long-term Q5$_0$	
	LTQ_{84}-AQ_{84}	For each year, the difference between that year's Q_{84} and the long-term Q_{84}	
	LTQ_{90}-AQ_{90}	For each year, the difference between that year's Q_{90} and the long-term Q_{90}	
	Number of times exceeded Q_5(nQ_5)	Number of times in a year that discharge rises above LTQ_5 (not number of days but number of times)	nQ_5
	Number of times exceeded Q_{16} (nQ_{16})	Number of times in a year that discharge rises above LTQ_{16} (not number of days but number of times)	nQ1$_6$
	Number of times exceeded Q_{50} (nQ_{50})	Number of times in a year that discharge rises above LTQ_{50} (not number of days but number of times)	nQ_{50}
	Number of times exceeded Q_{84} (nQ_{84})	Number of times in a year that discharge rises above LTQ_{84} (not number of days but number of times)	nQ_{84}
	Number of times exceeded Q_{90} (nQ_{90})	Number of times in a year that discharge rises above LTQ_{90} (not number of days but number of times)	nQ_{90}
Variability	**Annual Range (yearly) of Q**	For each year (e.g. max discharge 1967 - min discharge 1967) We will end up with 46 values of range.	YAN
	Standard Deviation (yearly) of Q	For each year	YSD
	Coefficient of Variation (yearly) of Q	For each year (standard deviation of all the daily flow values, divided by the mean annual flow).	YCV
	Annual Range (long-term)	For all years (e.g. mean max discharge of 1967–2017 - mean min discharge 1967–2017)	LTAN
	Standard Deviation (long-term)	For all years	LTSD
	Coefficient of Variation (long-term)	For all years	LTCV
Timing	**Timing of Q_5 in a year**	The Julian Day for the longest period of time that Q_5 was exceeded. (e.g. 20th of July = 220)	TQ > 5
	Timing of Q_{16} in a year	The Julian Day for the longest period of time that Q_{16} was exceeded. (e.g. 20th of July = 220)	TQ > 16

	Timing of Q_{84} in a year	The Julian Day for the longest period of time that Q was less than Q_{84}. (e.g. 20th of July = 220)	TQ < 84
	Timing of Q_{90} in a year	The Julian Day for the longest period of time that Q was less than Q_{90}. (e.g. 20th of July = 220)	TQ < 90
Rate	**Rise rate for each year**	Mean of all positive differences between consecutive daily values (single value for each yea3r)	YRR
	Fall rate for each year	Mean of all negative differences between consecutive daily values	YFR
	Rise rate for long-term	Mean of all positive differences/51 years	LTRR
	Fall rate for long-term	Mean of all negative differences/51 years	LTFR
	Rise rate for each month	Mean of all positive differences of a particular month (e.g. positive difference in January 1967 + positive difference in January 1968../51 Januaries)	MRR
	Fall rate for each month	Mean of all negative differences of a particular month (e.g. negative difference in January 1967 + negative difference in January 1968../51 Januaries)	MFR

APPENDIX A2

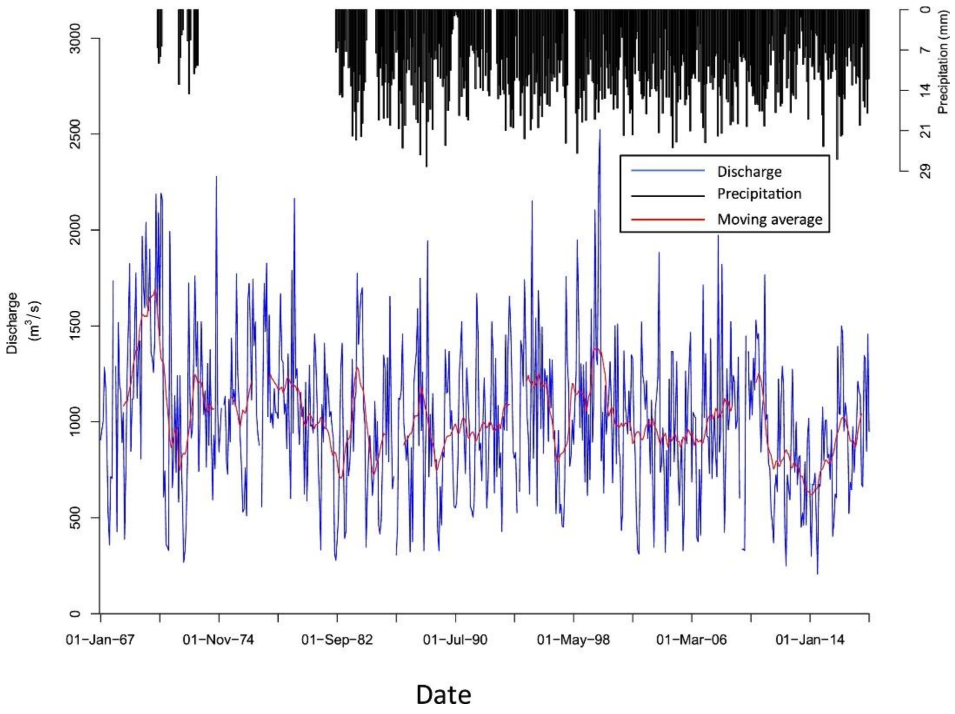

Fig. A2 Mean daily rainfall per month (Nanga Entawau station) and monthly discharge (Telok Buing station) of the Baleh River from 1967-2017 (see Fig. 3.2 for location details).

APPENDIX A3

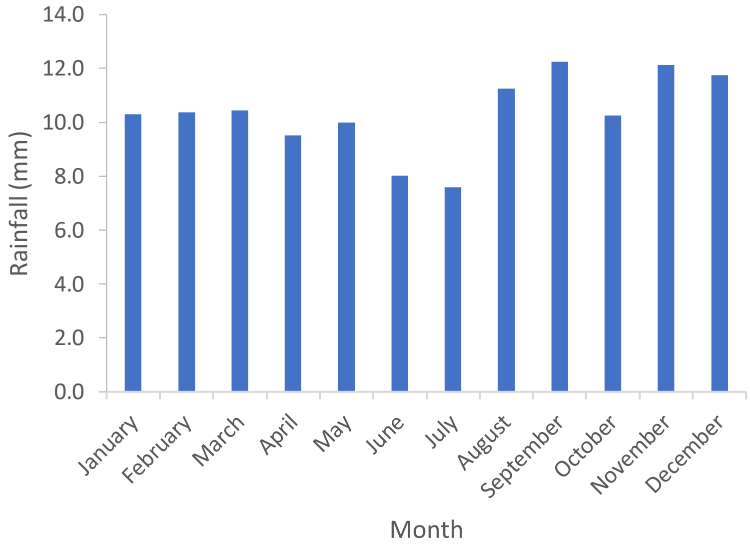

Fig. A3 Mean daily rainfall per month at Nanga Entawau (1967-2017).

APPENDIX A4

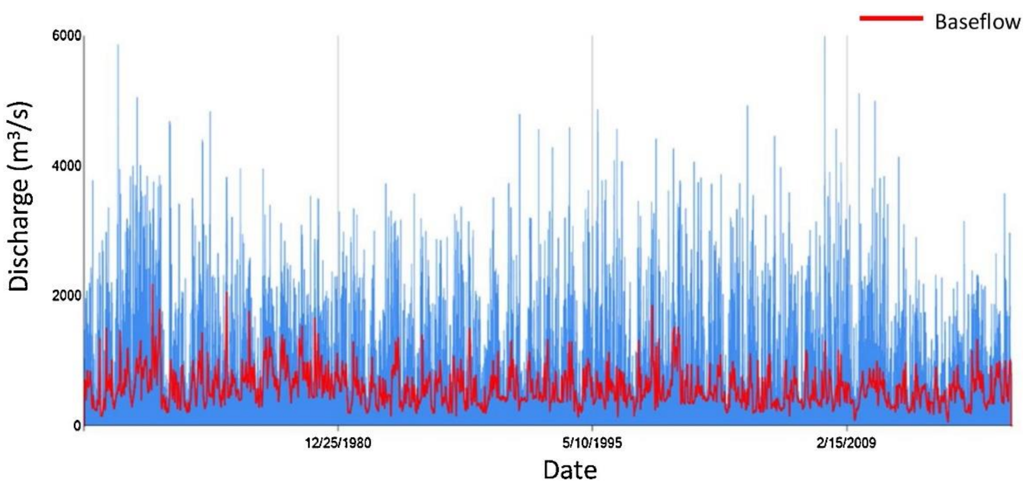

Fig. A4 Baseflow diagram of the mean daily flow time series (1967-2017).

APPENDIX A5

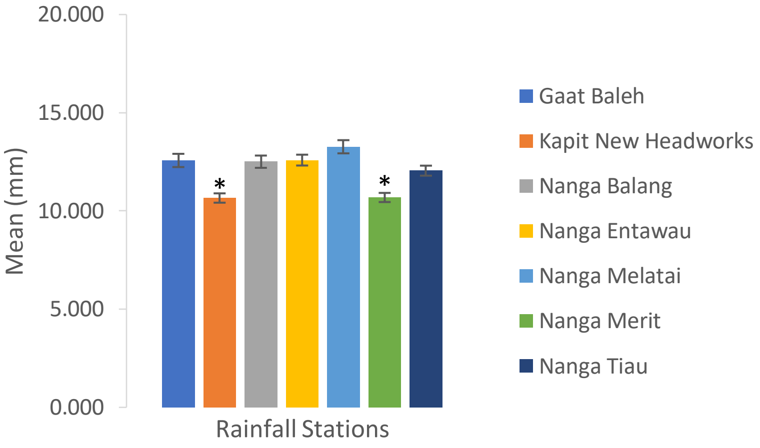

Fig. A5 Mean daily rainfall per month for each station along with results from ANOVA post-hoc test. The asterisk (*) above the bar indicates that the station is significantly different from the other stations ($p<0.05$).

APPENDIX A6

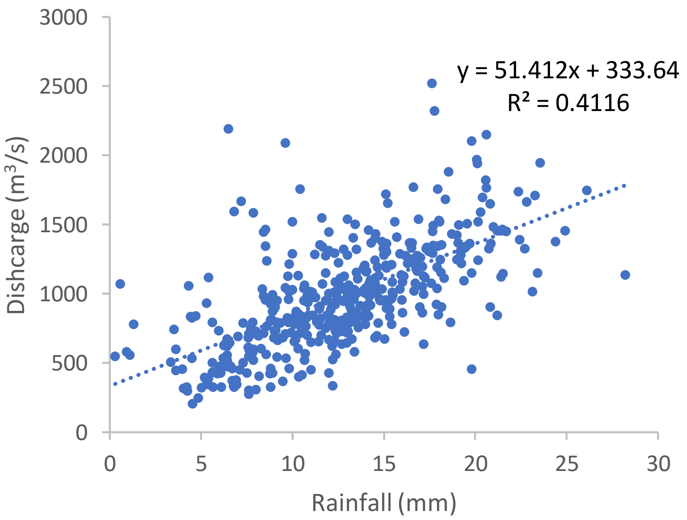

Fig. A6 Linear regression between mean daily rainfall per month and discharge at Telok Buing. For this regression, the value of rainfall used is the average of that at the 4 upstream rainfall stations (Nanga Entawau, Gaat Baleh, Nanga Balang, Nanga Melatai). This averaging method was used simply because there was no significant difference between the spatial variations between the stations.

Appendix A7

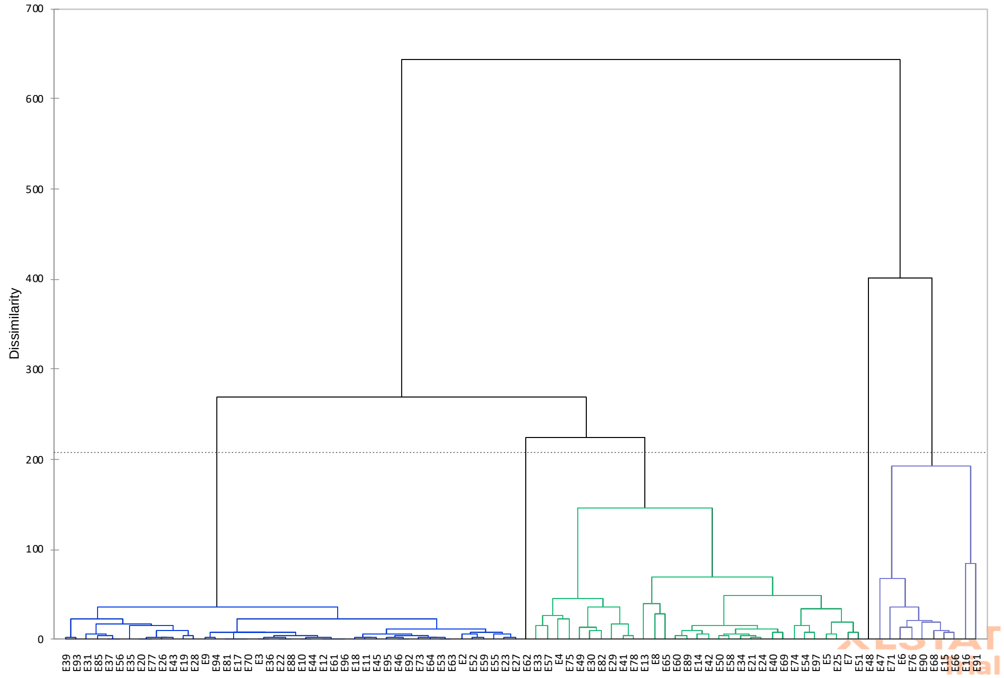

Fig. A7 Dendrogram of the grouped events produced by AHC.

Appendix A8

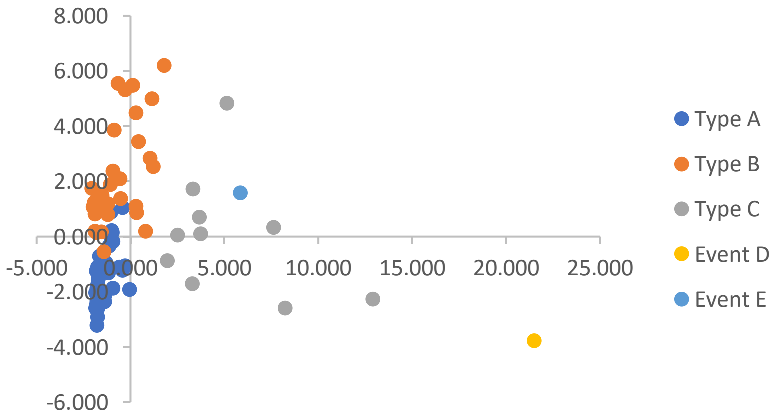

Fig. A8 PCA of high flow events, colour coded according to groups identified by the AHC cluster analysis.

APPENDIX A9

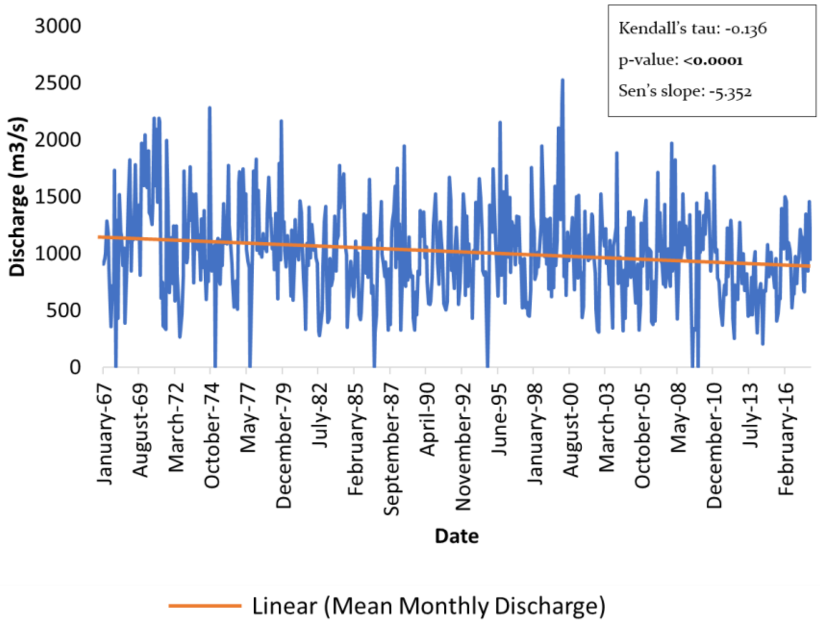

Fig. A9 Time series of the mean daily flow by month over 51-year data period.

APPENDIX A10

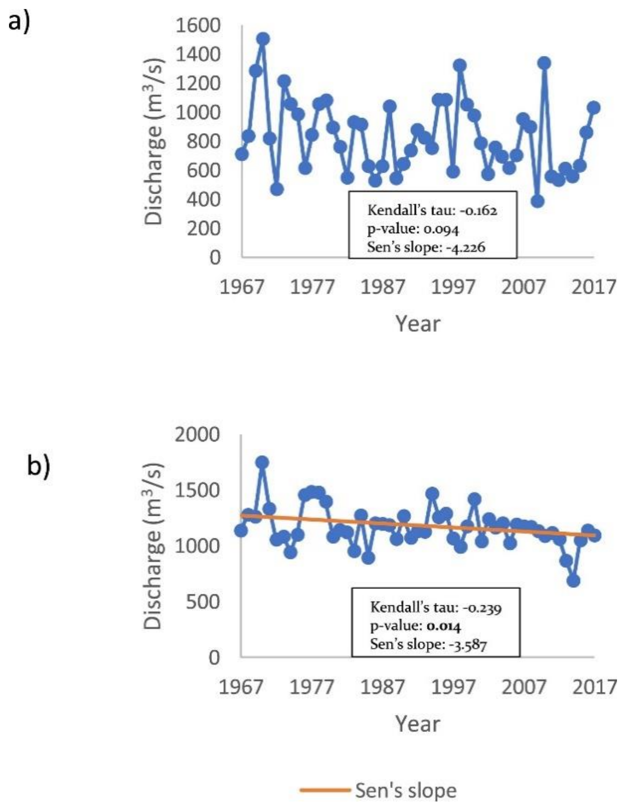

Fig. A10 Time series of the mean discharge in the (a) dry and (b) wet periods over 51 years.

APPENDIX A11

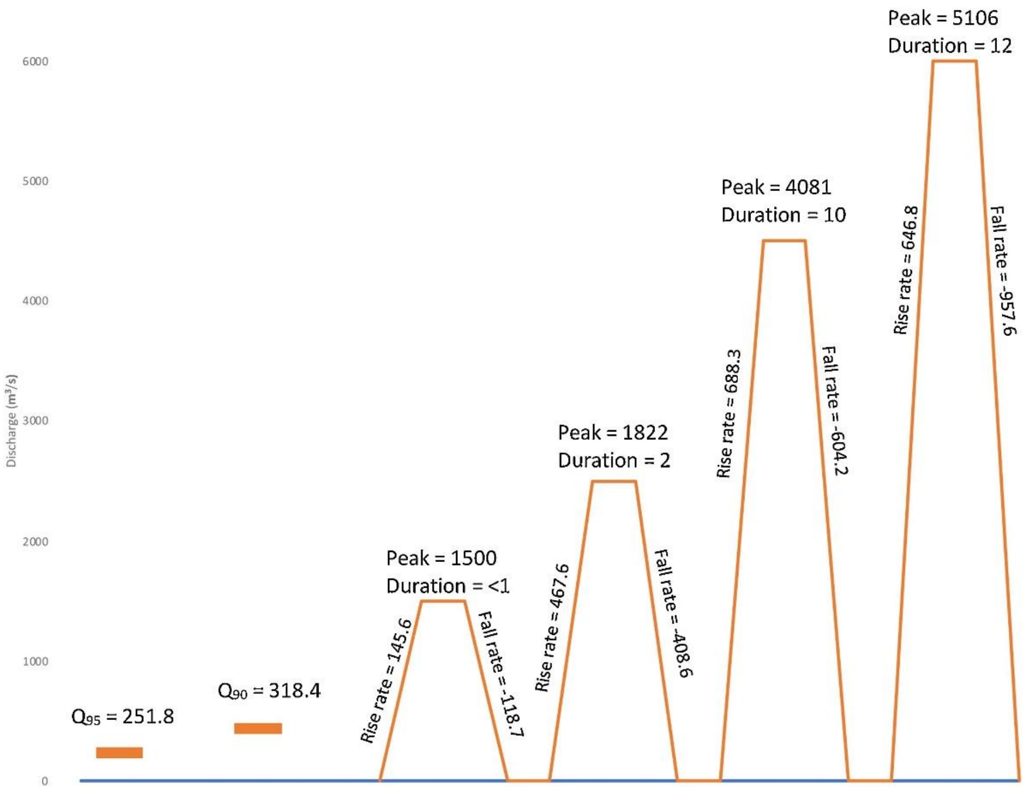

Fig. A11 Schematic diagram of key traits of the flow classes.

CHAPTER 4

Connectivity Changes in a Large Tropical River Basin After Damming & Deforestation: A Prospective Approach

4. Connectivity Changes in a Large Tropical River Basin after Damming and Deforestation: A Prospective Approach

Abstract

This chapter evaluates changes in connectivity across the Baleh catchment in response to various anthropogenic pressures. Connectivity was assessed using the Sediment Connectivity Index (IC), a model that quantifies structural connectivity using spatially explicit data on gradient and roughness across the catchment. IC values were calculated at two scales. First, connectivity between the whole of the catchment area and its downstream confluence with the Rajang River was calculated for historical, current and some future scenarios; scenarios included forest clearance, damming and road construction. Change was assessed by subtracting IC values for each scenario from those of the current one. Second, the effects on connectivity of managing the reservoir to maintain two different lake levels were assessed. This involved modelling only the area upstream from the dam, with connectivity values between hillslopes, and both the lake perimeter and the river channel calculated.

IC models suggested that historical changes in landcover (most recent 20-year period) have not altered connectivity between the Baleh and the Rajang markedly. Differences in IC between the current and 2001 landcover were minimal. Future roads and forest clearance of 10% were predicted to have detectable impacts on connectivity between the Baleh and Rajang, with small decreases and increases in IC respectively related to these changes. However, models suggested that once the dam is built the effects of the impoundment on connectivity will swamp those of roads and landcover change, with a major portion of the Baleh becoming disconnected from the Rajang. Operation of the

dam will have implications for IC upstream of the dam because of how different lake levels/areas alter connectivity. Larger lake areas impact IC most, and so managing water levels in ways to reduce changes in connectivity is suggested as a possible way of controlling the dam's impacts on connectivity in the upper basin.

4.1. Introduction

Internal linkages related principally to topography (gradient) and roughness (impedance to movement) influence the sensitivity of geomorphic systems to natural and anthropogenic pressures. In catchment systems, analysis of sediment connectivity can be used to help understand these linkages and, in turn, the sensitivity of the landscape to pressures. Sediment connectivity can be defined as "the degree to which a system facilitates the transfer of sediment through itself by means of coupling relationships between its components" (Heckmann et al., 2018). Sediment connectivity can be investigated in a hillslope to channel perspective (lateral connectivity *sensu* Fryirs et al., 2007), or along the channel network (longitudinal connectivity *sensu* Fryirs et al., 2007). Connectivity depends on the structural characteristics of the surfaces (e.g. their topography, roughness) and the dynamics of the processes controlling hydrologic and sediment fluxes within the system (functional connectivity *sensu* Wainwright et al., 2011). These structural and functional characteristics determine the sediment balance at multiple temporal scales and, consequently, the evolution of landforms and changes in landscape properties (Bracken et al., 2015).

Connectivity varies over time and space due to the interactions between external forcing (mainly precipitation and temperature), landscape properties (i.e. structural connectivity), and the magnitude of water and sediment fluxes (i.e. functional connectivity) that determine the frequency, distribution and scale of erosional and sedimentation processes. In tropical regions, various development pressures are driving landcover and land use changes that see originally forested catchments being cleared for agriculture (notably conversion to oil palm) or urban or industrial development (Lambin et al., 2003; Hartemink et al., 2008). Tropical regions are also witnessing a major growth in dam construction (Chong et al., 2021a), with many large dam projects proving controversial due to their social and environmental impacts (Fearnside, 2016). These developments are invariably accompanied by the required infrastructure, most notably road networks, which bring additional impacts on the landscape (Goman and Byrne, 1998). Many tropical rivers now run perpetually brown due to high suspended sediment loads (Nainar et al., 2015), indicative of a high base level supply of fine sediments that can be transported in suspension as well as increased loads resulting from landcover change.

Dams and landcover changes create either barriers or buffers (Fryirs, 2007) that alter structural connectivity and have a direct impact on the transfer of fine sediment along river channels. This may increase in-channel sedimentation, change bed porosity through clogging, and alter the riverine habitat (Buendia et al., 2013). However, the effects of such dams and landcover change on structural connectivity have rarely been assessed in tropical catchments, though changes in sediment loads have been quantified through application of models such as SWAT® (Vijith et al., 2018). This knowledge gap is significant due to the high biodiversity and ongoing pressures on tropical freshwater systems (Sundar et al., 2020), and the fact that the effects of changes to connectivity on river sediment loads in these climate zones may be different from others due to the high and intense precipitation, and the nature of tropical soils which make them susceptible to erosion (Clark et al., 2017).

Advances have been made in quantifying and modelling sediment connectivity, with morphometric, GIS-based methods (Heckmann et al., 2018) now providing a feasible approach for detailed evaluation of connectivity over large surfaces catchments, including inaccessible areas (e.g. very steep mountain headwater basins) that would be hard to monitor with field instrumentation. The availability of remote sensing data sets enables the analysis of spatio-temporal variability in connectivity over long time periods (Meßenzehl et al., 2014), and simulate potential changes associated with changes on topography and roughness that human pressures may cause such as the construction of dams or roads. Raster-based indices provide an opportunity to quantitatively assess the spatial distribution of sediment connectivity. The Sediment Connectivity Index (IC; Borselli et al., 2008; Cavalli et al., 2013; Heckmann et al., 2018) is one such raster-based tool. This index was developed by Borselli et al. (2008), and later modified by Cavalli et al. (2013), and has been widely applied in temperate and Mediterranean regions (e.g. Goldin et al., 2016; Ortíz-Rodríguez et al., 2017; Persichillo et al., 2018; López-Vicente et al., 2019).

Within this context, in this chapter, IC is applied to a large, forested, upland tropical river basin (the Baleh, Sarawak, Malaysian Borneo; catchment area 5,625 km^2). The Baleh is the major upper tributary of the Rajang, Malaysia's longest river. The Rajang River is the main drainage system for central Sarawak, with a catchment area of approximately 52,010 km^2 (DID, 2017). Its position as the country's longest river makes it a culturally significant and iconic system, but it also supports important biodiversity (e.g. one of the key habitats for the Irrawaddy dolphin, and mangroves along the river are home to a large variety of fish, crabs, shrimps and shellfish; Bali et al., 2017; Noweg et al., 2023). A large dam is currently being constructed in the upper part of the Baleh and is due for completion in 2026. On the one hand, dams trap sediment (e.g. Williams and Wolman, 1984; Vericat and Batalla, 2006; Maeck et al., 2013; Kondolf et al., 2014a) so there are self-evident implications of the impoundment for connectivity across the Baleh and, in turn, the connection between this system and the Rajang. Dam construction has required access roads to be built in previously undisturbed parts of the catchment, which themselves may further reduce connectivity (e.g. van der Waal and Rowntree, 2018; Zhao et al., 2022). On the other hand, increased access resulting from such roads may lead to forest clearance and disturbance, as has been observed in many areas (Llena et al., 2019; Zhao et al., 2022), and this may increase connectivity between hillslopes and river channels.

The work described in this chapter aimed to understand how these developments interact to alter patterns of connectivity across the Baleh, and between the Baleh and the Rajang. It also had a more specific focus on understanding how management of water levels in the reservoir might impact connectivity because of differences in the extent of inundation (i.e. change in base levels). The work had four objectives: (i) to assess how historical changes in landcover have altered patterns of connectivity across the catchment, (ii) to assess how the dam, road construction and forest clearance each influence connectivity between the Baleh catchment and the river's confluence with the Rajang, (iii) to evaluate the combined ('net') effects of the dam, road construction and deforestation on spatial patterns of connectivity across the catchment, and (iv) to assess how operating the dam to maintain different water levels influences pattern of connectivity across the area inundated by the lake. We tested three hypotheses: (i) forest clearance and road construction increase and decrease structural connectivity respectively, (ii) the dam has a marked effect on connectivity, disconnecting the Rajang from large parts of the upper Baleh, with these effects overriding those associated with forest clearance and road construction, and (iii) high water levels in the reservoir increase connectivity across the sub-catchments draining into the reservoir. Hypotheses I and II use the Baleh-Rajang confluence as the target, while Hypothesis III uses the reservoir and stream network upstream from the dam as targets. To test these hypotheses, we modelled sediment connectivity for current and a number of post-dam scenarios using the IC developed by Cavalli et al. (2013).

4.2. MATERIALS AND METHODS

4.2.1. STUDY AREA

The Baleh (Figure 4.1a) is one of two main sub-catchments within the Rajang basin and makes up approximately 10% of the Rajang's catchment area. The Rajang flows from east to west in Sarawak, originating from the Nieuwenhuis Mountain Range and the upper Kapuas Mountains, eventually discharging into the South China Sea (MacKinnon, 1996). The catchment ranges from sea level up to around 2000 m a.s.l. (Milliman and Farnsworth, 2013). The main settlements along the river are the towns of Kapit, Kanowit and the city of Sibu (163,000 inhabitants). The Baleh-Rajang confluence, despite being approximately 180 km from the sea, sits at only 10 m a.s.l. Floodplains in the Baleh, when present, are of limited area (Staub and Gastaldo, 2000). Geology consists of sandstone and shale from the Belaga and Nyalau Formations (Ling et al., 2016). The Baleh River generally consists of trellis to dendritic drainage patterns. Drainage patterns are influenced by folded strata of the interbedded sandstone–shale, and the joint and fault systems that are intersecting perpendicularly to the east-west trending beds. The upstream part of the Baleh of the study area is underlain by igneous rocks, and a more dendritic drainage pattern (Muol and Noweg, 2018). Soils are mainly Red Yellow Podzols (Sarawak classification system; Tie, 1982). Land cover in the catchment is predominantly hill forest, comprising mixed dipterocarp and secondary forest (Figure 4.1b). Annual total rainfall is among the highest in Sarawak, exceeding 5000 mm in most years. There is usually an average of around 250 days of measurable precipitation each year. The highly frequent and often intense precipitation is significant for structural connectivity because of its effects on the soil surface. Temperature is high throughout the year, with a mean annual temperature of 33˚C (Chong et al., 2021b).

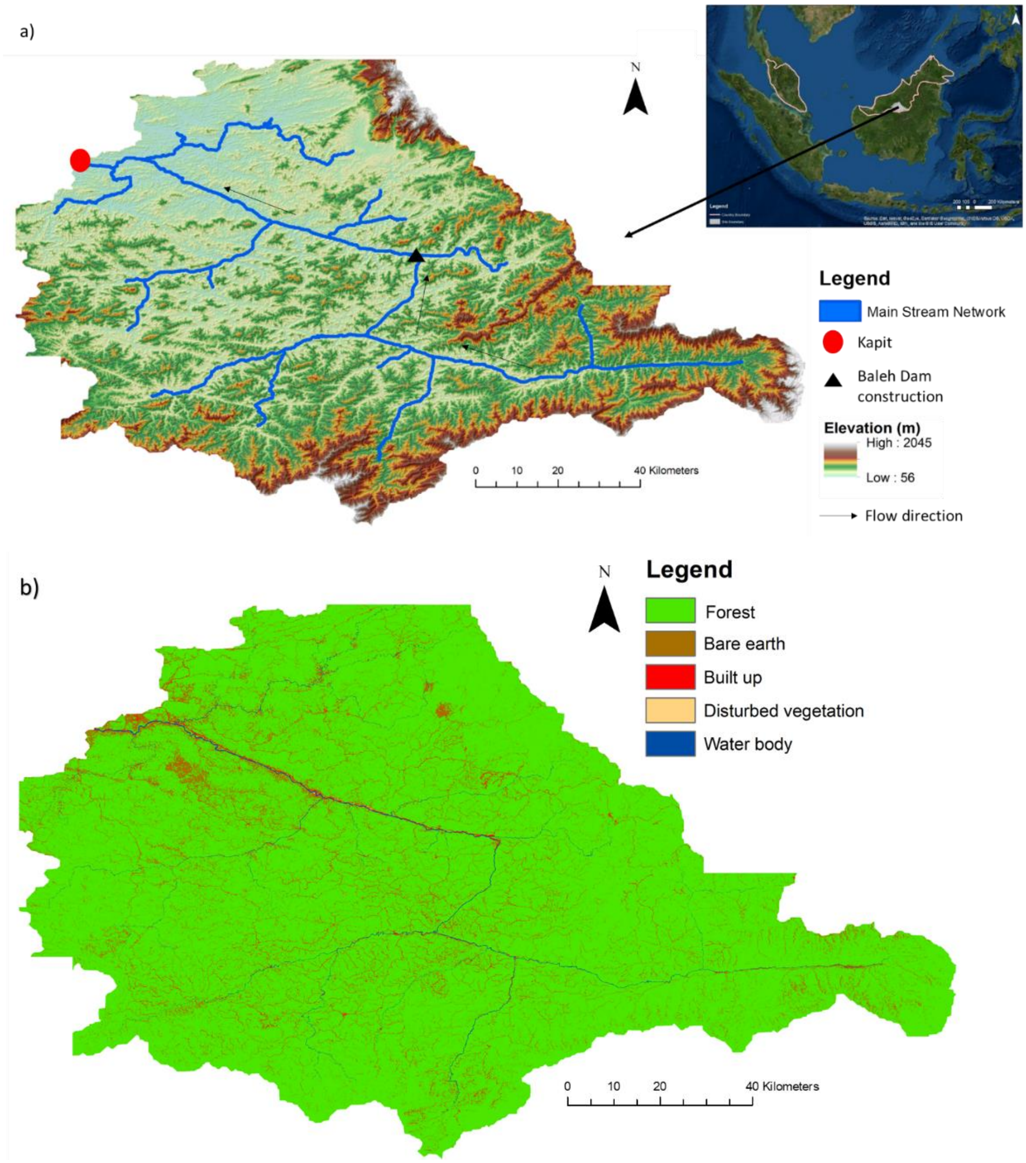

Figure 4.1 (a) Location, topography, stream network and (b) landcover (2019) of the Baleh catchment. N.B. There is a small area on the upper part of the catchment missing but this does not affect to the analyses.

4.2.2. Computation of Sediment Connectivity

Sediment connectivity was modelled using the IC (Borselli et al., 2008; Cavalli et al., 2013). The IC expresses the potential connection between catchment compartments. Connectivity can be assessed based on single target or different targets. This allows the assessment of the potential connection between sources (hillslopes) and features of interest such as, for instance, the outlet of a catchment, along a river channel or lake. The IC is defined as:

$$IC = log_{10}(\frac{D_{up}}{D_{dn}}) \quad (1)$$

where D_{up} and D_{dn} are respectively the upslope and downslope components of connectivity. IC is defined in the range of [-∞, +∞], with connectivity increasing for larger IC values. The upslope component D_{up} is the potential for downward routing of the sediment produced upslope and is estimated as follows:

$$D_{up} = \overline{W}\bar{s}\sqrt{A} \quad (2)$$

where $\overline{W}$ is the average weighting factor of the upslope contributing area (see Section 4.2.3.2 for further details), $\bar{s}$ is the average slope gradient of the upslope contributing area (m/m) and A is the upslope contributing area (m^2). The downslope component, D_{dn} considers the flow path length that a particle must travel to arrive to the nearest target or sink and it is expressed as:

$$D_{dn} = \sum_i \frac{d_i}{\overline{W}_i \bar{s}_i} \quad (3)$$

where d_i is the length of the flow path along the i^{th} cell according to the steepest downslope direction (m), $\overline{W}_i$ and $\bar{s}_i$ are the weighting factor and the slope gradient of the i^{th} cell, respectively.

4.2.3. Study Scales and Elements of Analysis

For ease of analysis and interpretation, the basin was divided into a manageable number of sub-catchments delineated with tributaries draining an area with threshold values of more than 250 km^2 and, where the valley morphology is more confined, a lower area threshold value of 20 km^2. The reason of having two different threshold values is to include those small tributaries which drainage areas do not exceed the larger threshold value of 250 km^2 along the main channel where the valley confines the river with the objective to see how the spatial patterns of change in connectivity varies with these two types/sizes of sub-catchment. With heterogeneous sized sub-catchments, some area-related trends might arise. It is reasonable in fact that small catchments directly draining into the main target will most likely manifest higher IC values with respect to the larger catchments and this might be primarily related to their size and their distance from the target. These size criteria generated 10 independent sub-catchments (>250 km^2) and 25 independent small sub-catchments (>20 km^2) to provide insights into connectivity across the basin as a whole (Figure 4.2) and the impacts of damming, roads and landcover change on connectivity.

The connectivity targets (i.e. shapefiles) were different for Hypotheses I and II compared to III. In effect, this meant that connectivity was assessed at two different spatial scales. The whole Baleh catchment was of interest for Hypotheses I and II, and so this work used the basin outlet (confluence with the Rajang) as the target in order to assess how the developments affected connectivity between the Baleh and Rajang. All scenarios at this scale are grouped under what we refer to as ‘IC 1’. For Hypothesis III, impacts of two lake levels are modelled: a low level (i.e. 87 m at the dam wall) and a full level (i.e. 175 m at the dam wall). This modelling was only done for the area upstream from the dam, with the river and the lake perimeter as targets, i.e. each cell of the catchment is calculated in relation to these target features (river channel and lake perimeter); accordingly, these targets allow evaluation of lateral (hillslope to channel) connectivity based on different base levels imposed by the lake. Scenarios at this scale are referred to as IC 2.

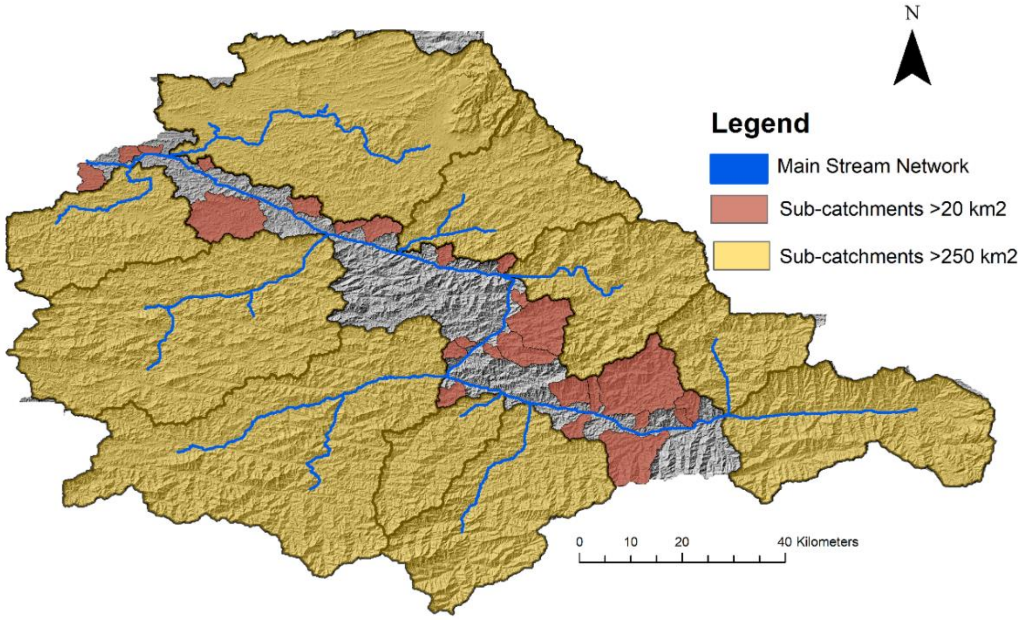

Figure 4.2 The small and big sub-catchments of the Baleh with threshold values of 20 km^2 and 250 km^2 respectively.

4.2.3.1. TERRAIN DATA

Topography determinates the slope and the drainage network characteristics, and both parameters are considered in the calculation of the upslope and downslope components of the IC. Topography was parameterised by means of Digital Elevation Models (DEMs).

DEMs were obtained based on the ASF DAAC datasets provided by the NASA Earth Science Data and Information System© (ESDIS) project (available at: https://search.asf.alaska.edu/#/). To analyse sediment connectivity, six DEMs were used:

(i) The 2008 DEM provided by the NASA-ESDIS (12.5 m resolution). This was considered the current DEM, being representative of the pre-dam conditions.

(ii) Five DEMs representing the terrain after dam and road construction (future scenarios). They were produced by modifying the current DEM. Elevation changes were made to the area of the dam and along routes of roads currently under construction and likely future ones. These scenarios planned are described in more detail in Section 4.2.2.3 (Figure 4.3). Information on future potential reservoir levels and related flooded areas were obtained from and cross-checked with Sarawak Energy Berhad, the company in charge of the construction of the scheme.

In the following sections, the process of obtaining the weighting factors is presented and the different scenarios considered to evaluate changes on connectivity due to dam construction and land use changes are described. Finally, the analysis of these changes in terms of connectivity is presented.

4.2.3.2. Weighting Factor

The weighting factor, which appears in the upslope and downslope components of IC, represents the impedance to runoff and sediment fluxes due to properties of the land use and soil surface. Impedance was expressed by Manning’s n roughness coefficient.

In the original IC (Borselli et al., 2008), the C-factor based on USLE-RUSLE models was used to parameterise the weighting factor (W). However, in studies like the one presented here (see below for specific references), where the evaluation of the role of different vegetation cover and land use changes on sediment connectivity is one of the main objectives, an alternative approach to the C-factor is using a parameter related to hydraulic roughness. Roughness is needed for a better representation of the impedance to the water and sediment fluxes since the C-factor only refers to cover and management related to erosion. An option is to use the Manning's n roughness coefficient (n), which represents the resistance to flow, with values varying according to different surface characteristics affecting roughness (e.g. Goldin, 2015; Heckamnn et al., 2015; Persichillo et al., 2018, Llena et al., 2019). For this study, an image classification on image composites was performed using Google Earth Engine© to obtain land use maps. A different Manning's n value was assigned to each of the land use classes, based on Goldin (2015). It is important to highlight that the number of land use classes was determined based on the quality (e.g. sharpness), characteristics (e.g. number of bands) and resolution (i.e. pixel size) of the aerial images used for the classification; the images with most limiting conditions (i.e. usually historical images) determined the number of final classes. In this case, we defined five different classes representing the main land uses of the study sub-catchments: forest, bare earth, built up, disturbed vegetation, and water bodies (with respective Manning's n values of 0.4, 0.15, 0.02, 0.25 and 0.001). The weighting factor W is subsequently computed as $W = 1 - n$ (following Goldin, 2015; and further e.g. Persichillo et al., 2018).

4.2.3.3. Scenarios of Change

Twelve different scenarios were designed and their impacts on connectivity were modelled. The 12 scenarios were grouped into two broad classes: (i) present and historical conditions, and (ii) future conditions. (i) uses the current and historical landcover and terrain data, while for (ii), changes to terrain and landcover data were made to reflect combinations of the presence of the dam, various roads, and forest loss. Table 4.1 and Figure 4.3 provide details of each scenario. As indicated in Table 4.1, for future conditions, DEMs were modified to reflect the presence of the dam and/or roads, while the weighting factor was modified to reflect forest clearance.

The present condition represents the condition with no dam and no access road running between Kapit and the dam construction site. To see how current connectivity differs from the past, 200l landcover data were used. The future deforestation scenario modelled catchment conditions at a point 10 years into the future and assumed an annual rate of forest loss of 1% per year; thus, forest cover was reduced by 10% in each sub-catchment (see Table 4.1 for more information). The dam was bult into the future scenarios and used technical information (dam height etc) obtained from the operator Sarawak Energy Berhad (SEB). The effect of access roads with different widths on connectivity was modelled; widths of 12.5 m and 25 m were assessed, based field measurements of the road currently being constructed (12.5 m) and the desire to understand how a larger road might have a greater impact. All of these scenarios formed what we termed - IC 1, with the target being the confluence of the Baleh and the Rajang (Figure 4.3). The effect of different dam operational strategies on connectivity was assessed by modelling the effects of having the lake maintained at two different depths - 87 m and 175 m at the dam wall. These depths were again based on information provided by SEB and reflected different scenarios of rainfall, and hence inflows to the lake. The river and lake perimeter were the targets for this modelling, which is referred to as IC 2. Full details of each scenario can be found in Table 4.1.

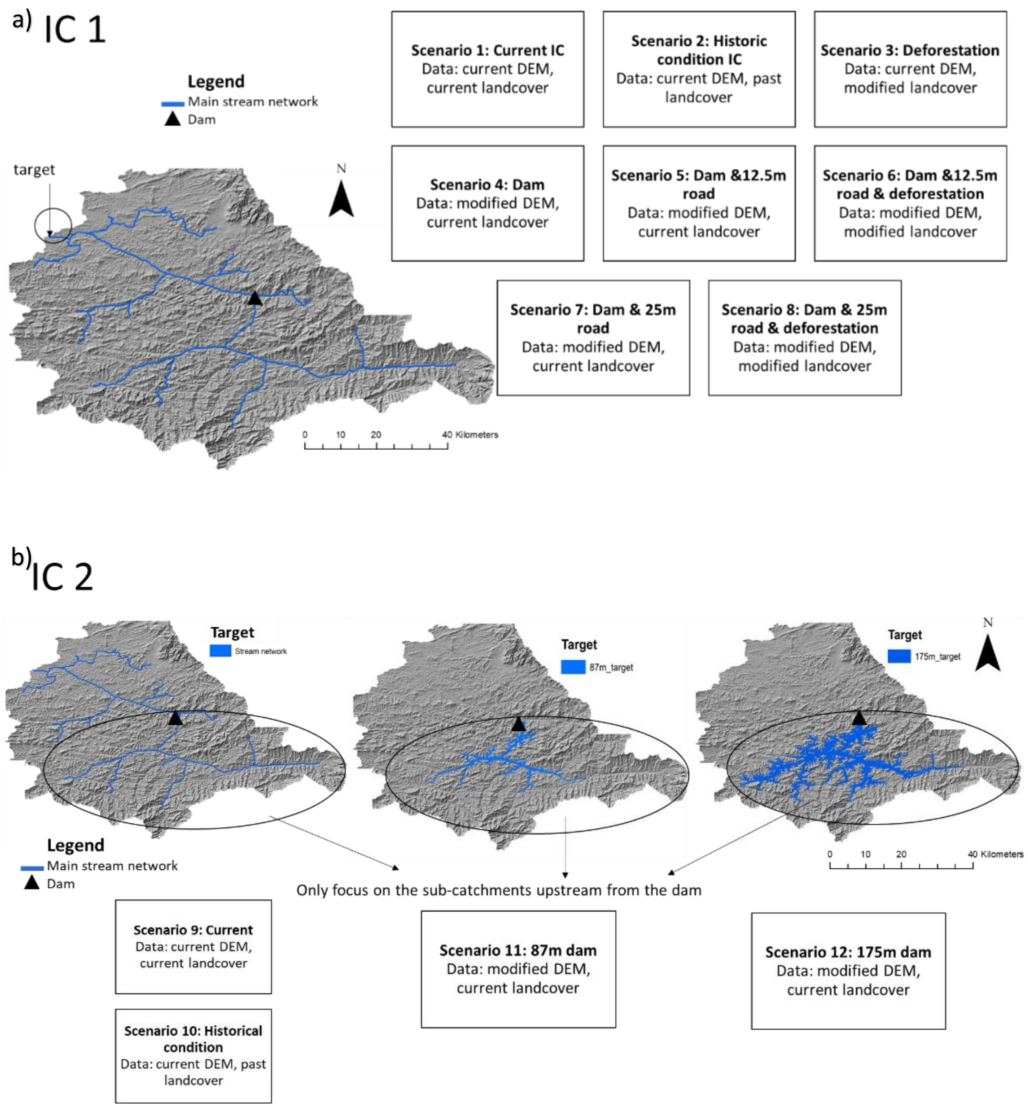

Figure 4.3 Summary of the (a) IC 1 and (b) IC 2 analyses.

Table 4.1 Modelled scenarios of changes (including present condition) of IC 1 and 2.

IC 1 (Target: Outlet)		
Scenario Code Number and Title	**Scale of Analysis**	**Justification**
(1) Present condition	Catchment	This scenario simply models IC for the current set of conditions in the catchment. It uses the most recent (2019) land cover imagery and satellite data. It does not include the dam nor the access road that is to be built running between Kapit and the dam construction site.
(2) Historical condition (2001)	Catchment	This scenario simply models IC for the past set of conditions in the catchment. It uses 2001 land cover imagery and satellite data.
(3) Deforestation only	Catchment	This scenario is to analyse the impact of deforestation on connectivity. The scenario involves modifying land cover in each of the sub-catchment, focusing on the areas nearer to the mainstem. We have tried to use a realistic degree of land cover change. Historically, in Baleh, the rate of land cover change has been quite low (0.2% per annum based on Lum (unpublished MRes thesis)). However, this low rate reflects the fact that the catchment has very limited access because there have been no roads. Accordingly, we need to apply a higher rate loss than this historic one because the access road is likely to result in more deforestation than previously observed. The average rate of deforestation across Sarawak is 0.6% per annum. We have therefore used this for the Baleh. Our scenario models catchment conditions at a point 10 years into the future and therefore, we have reduced forest cover by 10% (i.e. 1% per year for 10 years).
(4) Dam	Catchment	This scenario is to analyse the impact of the dam at full lake level on connectivity. The dam is currently under construction, and we have all the engineering/design information on the dam wall and reservoir storage capacity. This has allowed us to add the dam to the terrain data to simulate the effects of Scenario 4. The dam was created using a transverse polygon. This polygon was then converted into a raster, then merged with the original DEM for this scenario.
(5) Dam, and 12.5 m wide access road to the dam	Catchment	The construction of the dam requires an access road to be built from Kapit to the dam site. This is now largely completed though it is a dirt road and eventually will be tarmacked. Hence this is a definite scenario that we need to consider the effects of. We visited the site in March 2022 and travelled along the access road. Hence, we have a very clear idea of its route and dimensions. We can use this to help us modify the terrain to best reflect this new infrastructure. Note: This scenario uses the current land cover.

(6) Dam, and 25 m wide access road to the dam	Catchment	Same as above, but the width of the access road is larger.
(7) Dam, 12.5 m wide access road to the dam, and deforestation	Catchment	Same as above, but with 10% of deforestation in each sub-catchment along the mainstem.
(8) Dam, 25 m wide access road to the dam, and deforestation	Catchment	Same as above, but the width of the access road is larger.
IC 2 (Target: River channel)		
(9) Present condition	Sub-catchment	This scenario simply models IC for the current set of conditions in the catchment. It uses the most recent (2019) land cover imagery and satellite data. It does not include the dam nor the access road that is to be built running between Kapit and the dam construction site.
(10) Historical condition (2001)	Sub-catchment	This scenario simply models IC for the past set of conditions in the catchment. It uses 2001 land cover imagery and satellite data.
IC 2 (Target: 87 m lake level)		
(11) 87 m dam	Sub-catchment	This scenario is to analyse the impact of low lake level which is equivalent to 50% of the full level on connectivity. The dam is currently under construction, and we have all the engineering/design information on the dam wall and reservoir storage capacity. This has allowed us to add the dam to the terrain data to simulate the effects of Scenario 11. The dam was created using a transverse polygon. This polygon was then converted into a raster, then merged with the original DEM for this scenario. This lake level inundates an area of 180 km^2.
IC 2 (Target: 175 m lake level)		
(12) 175 m dam	Sub-catchment	This scenario is to analyse the impact of full lake level on connectivity. The dam is currently under construction, and we have all the engineering/design information on the dam wall and reservoir storage capacity. This has allowed us to add the dam to the terrain data to simulate the effects of Scenario 12. The dam was created using a transverse polygon. This polygon was then converted into a raster, then merged with the original DEM for this scenario. This lake level inundates an area of 588 km^2.

4.2.3.4. Changes in Sediment Connectivity

Once the IC maps were produced for each scenario, the degree of change in connectivity was analysed. Each scenario of change (Scenarios 2-12) is compared with the current scenario (Scenario 1) to identify the degree of change. This was done by subtracting the

IC-raster for each scenario from that of the current scenario. If the IC difference is negative (-), IC increased and vice versa. This approach follows the previous studies conducted by Llena et al. (2019) and Cucchiaro et al. (2019). IC difference maps and boxplots (Figure 4.4) for each scenario were generated to show spatial patterns and magnitudes of change.

The IC difference values were classified into five categories to ease interpretation of the results, following Llena et al. (2019) (Table 4.2). An IC Difference of -0.01 to 0.01 was used to represent No Change, while the mean value plus two times the standard deviation of the IC values was used to define the threshold between the Moderate Decrease and High Decrease classes. Finally, the mean value minus two times the standard deviation was the criterion used to establish the limit between the Moderate Increase and High Increase. The same criteria were used for the representation of the IC difference between all the analysed scenarios.

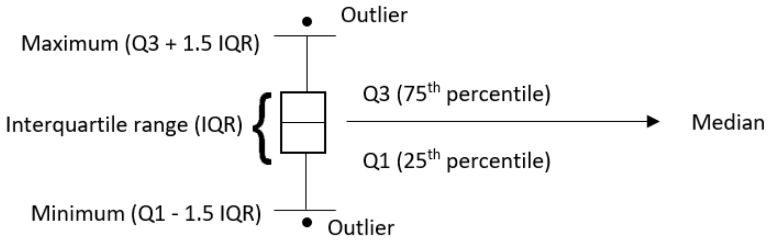

Figure 4.4 Schematic boxplot that is used to illustrate classification of changes in IC.

Table 4.2 Details of the classification scheme used to evaluate different magnitudes of change in IC.

Intervals	**Class**
- 0.01 to 0.01	No Change
Mean + (2 * Standard deviation) – (-0.01)	Threshold between High Decrease and Moderate Decrease
Mean – (2 * Standard deviation) + 0.01	Threshold between High Increase and Moderate Increase
> Mean – (2 * Standard deviation) + 0.01	High Increase
> Mean + (2 * Standard deviation) – (-0.01)	High Decrease

4.3. Results

4.3.1. Impacts of Historical Condition and Future Forest Clearance on Connectivity to the Catchment Outlet (Scenarios 1, 2 and 3)

An IC map of the present condition is presented in Figure 4.5. IC difference maps are presented in Figures 4.6-4.8 to show the spatial patterns of change in connectivity while Figures 4.9 and 4.10 provide an overview of the classification of change magnitudes.

In terms of connectivity between the Baleh and its confluence with the Rajang, the present condition (2019 landcover, i.e. Scenario 1) has an IC range of -4.7 to -6.6, with a mean ($\bar{x}$) of -6.29 and a standard deviation (SD) of 0.36. The lower parts of the catchment are more connected to the confluence than more upstream areas (i.e. red patches are more obvious at the downstream part of the catchment in Figure 4.5). The historical condition (2001 landcover, i.e. Scenario 2) has an IC range of -5.3 to -6.6, with $\bar{x}$ = -6.3 and SD = 0.29. Thus, there has been a slight increase in IC over the past 2 decades. This increase parallels the 3% drop in forest cover and 46% increase in the area of disturbed vegetation in 2019 compared to 2001 (Figure 4.6a). Disturbed vegetation is where natural vegetation has been altered/disturbed from its natural state but with some vegetation that remain.

Forest clearance (i.e. Scenario 3) resulted in an IC range of -4.7 to -6.6, with $\bar{x}$ = -6.28 and SD = 0.36. This range is very similar to the current scenario. However, High Increase in IC (2.5%) can be found in areas close to the channel as these patches of forests were converted to bare earth or built-up areas (Figure 4.6b).

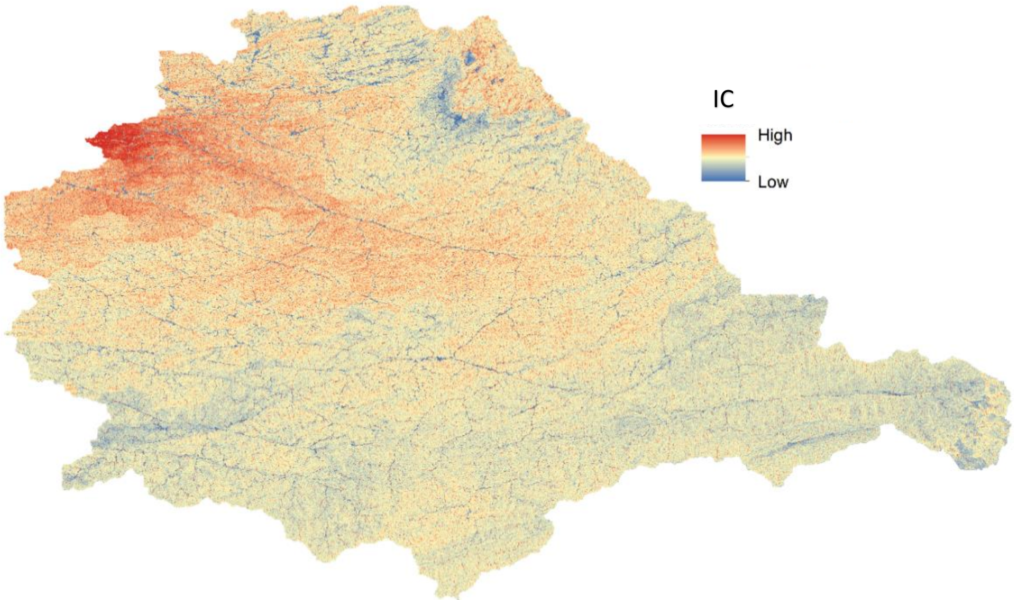

Figure 4.5 IC map of the present condition.

4.3.2. Impacts of Dam on Connectivity to the Catchment Outlet (Scenario 4)

IC values for the modelled dam scenario ranged from -4.7 to -7.2, with a $\bar{x}$ of -6.4 and a SD of 0.43 (Figures 4.6c, 4.9 and 4.10). This represents clear decrease in IC compared to the present (no dam) condition. This marked change in IC is seen across the sub-catchments upstream from the dam.

The dam scenario led to a 44% of decrease in IC but it is important to note that there is also a slight increase in connectivity at the sub-catchments downstream from the dam which is approximately 1%.

4.3.3. Impacts of Dam, Forest Clearance and Road Construction on Connectivity to the Catchment Outlet (Scenarios 5 – 8)

The IC for both 12.5 m and 25 m roads with the dam in place ranged from -4.7 to -7.2, with $\bar{x}$ = -6.4 and SD = 0.43. This range is similar to the IC range with only the dam in place. Thus, with the dam in place, the effects of the roads on connectivity are hardly detectable.

There were no clear distinctions in the IC difference values between the scenarios of 12.5 m road and 25 m road with dams. In general, there is a negligible effect of both road widths on the IC (i.e. only 0.0003% of increase in the area of the catchment with cells estimated to show High Increase in IC in the 25 m road scenario compared to the 12.5 m road scenario; Figures 4.6d and 6e). Overall, the impact of different road widths on catchment scale connectivity is therefore relatively less significant compared to the dam (Figure 4.7). Having said that, it is important to note that the modelling results show general IC trends around both road widths in which the IC values increase in the upslope area and decrease at the downslope area (Figure 4.8). The results also show that the roads trap sediment materials produced from the upslope areas, eventually decreasing downslope IC.

The IC for the modelled scenarios of combined effects of dam, forest clearance and road construction ranged from -4.7 to -7.2, with $\overline{x}$ = -6.39 and SD = 0.43 for both road widths. Similar to the IC range mentioned above, this shows that even with different road widths accompanied with 10% of forest clearance, the impact of these on connectivity is relatively less significant than the dam scenario at a catchment scale. There is only a slightly higher Moderate Increase of around 3% that may be related to the fact that some forested areas are being converted to bare earth (Figures 4.6f and 4.6g).

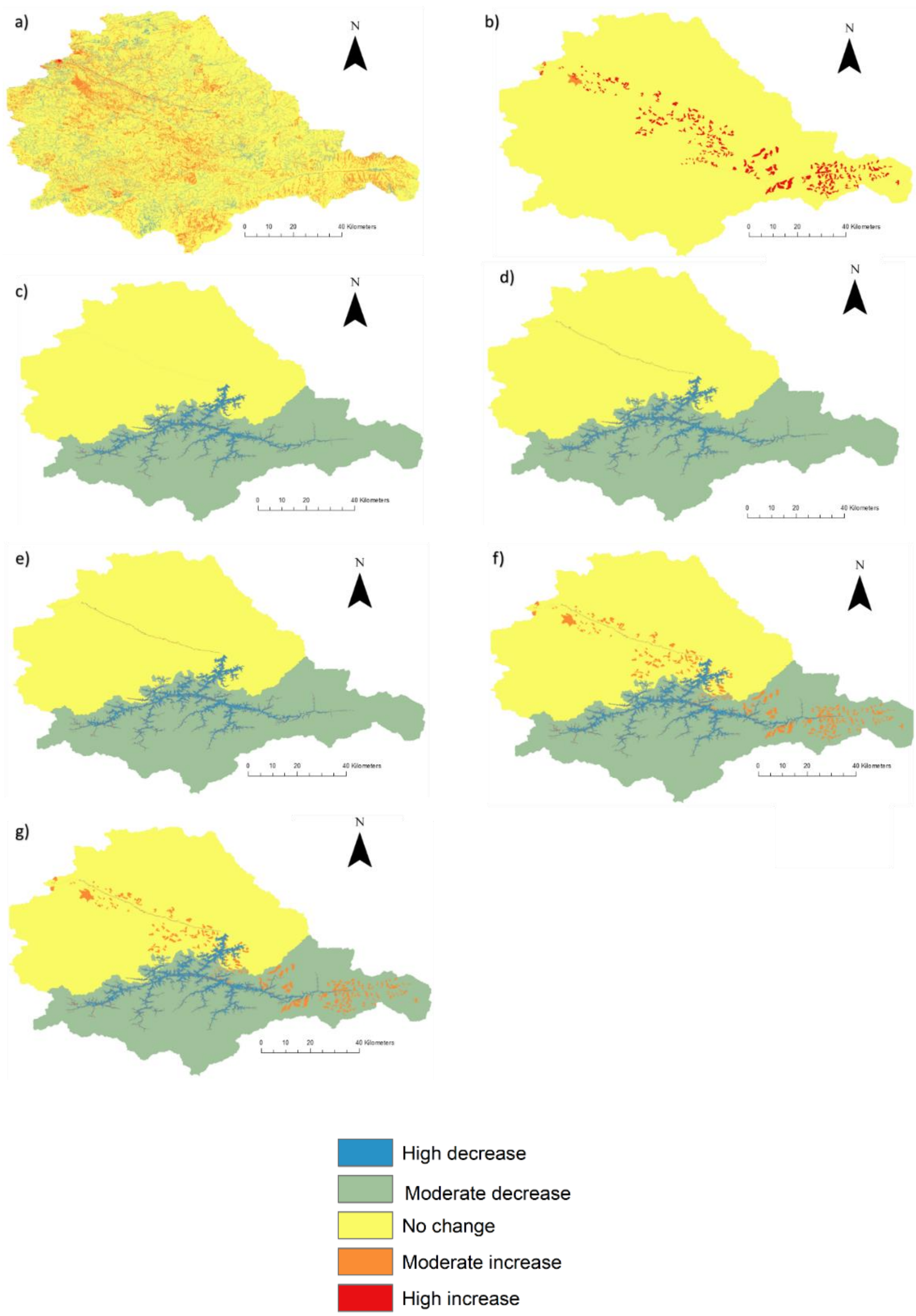

Figure 4.6 IC difference maps of (a) 2019-2001 landcover; (b) deforestation; (c) dam; (d) dam and 12.5 m road; (e) dam and 25 m road; (f) dam, 12.5 m road and deforestation; (g) dam, 25 m road and deforestation.

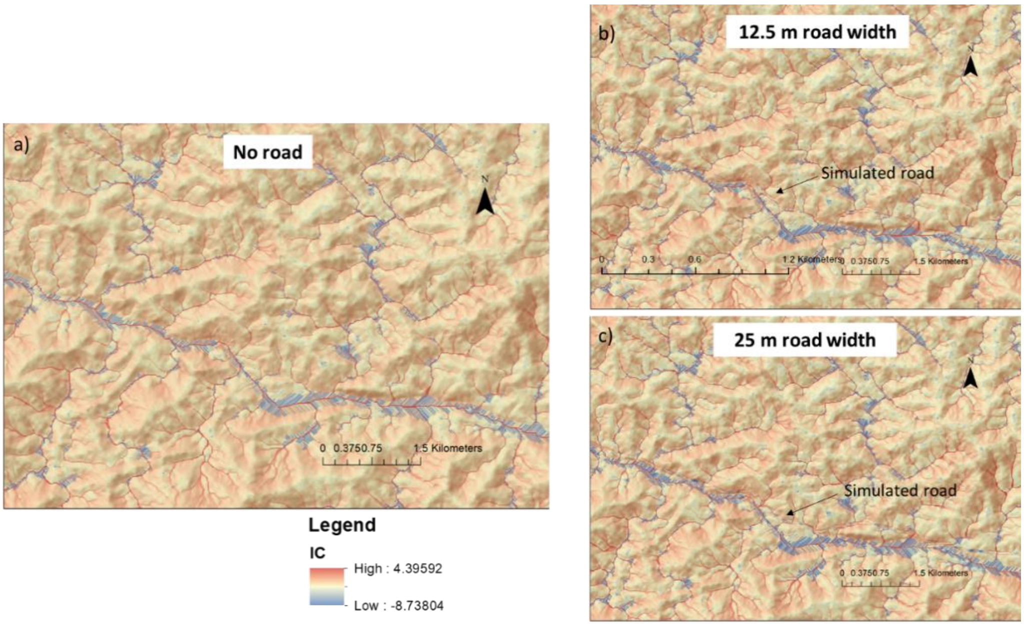

Figure 4.7 Snapshots of IC maps for (a) no roads, (b) 12.5 m road; (c) 25 m road.

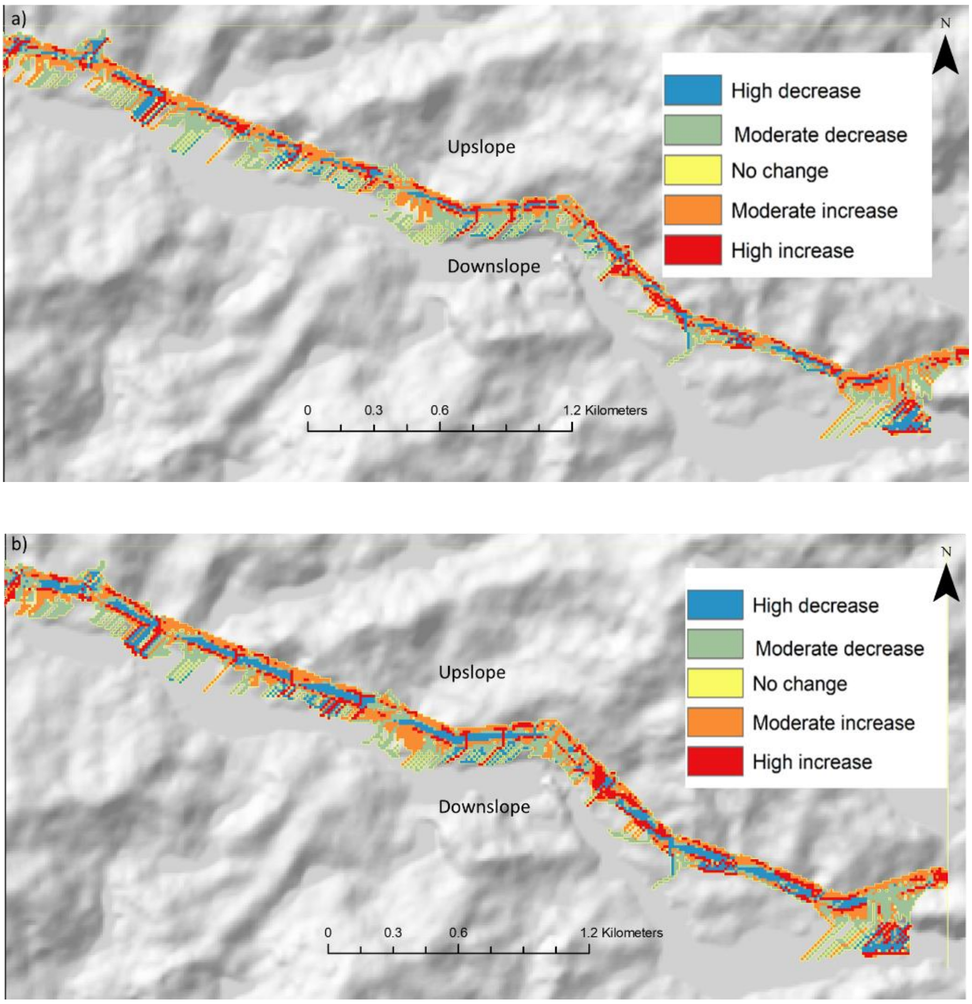

Figure 4.8 Snapshots of IC difference maps for (a) 12.5 m road; (b) 25 m road.

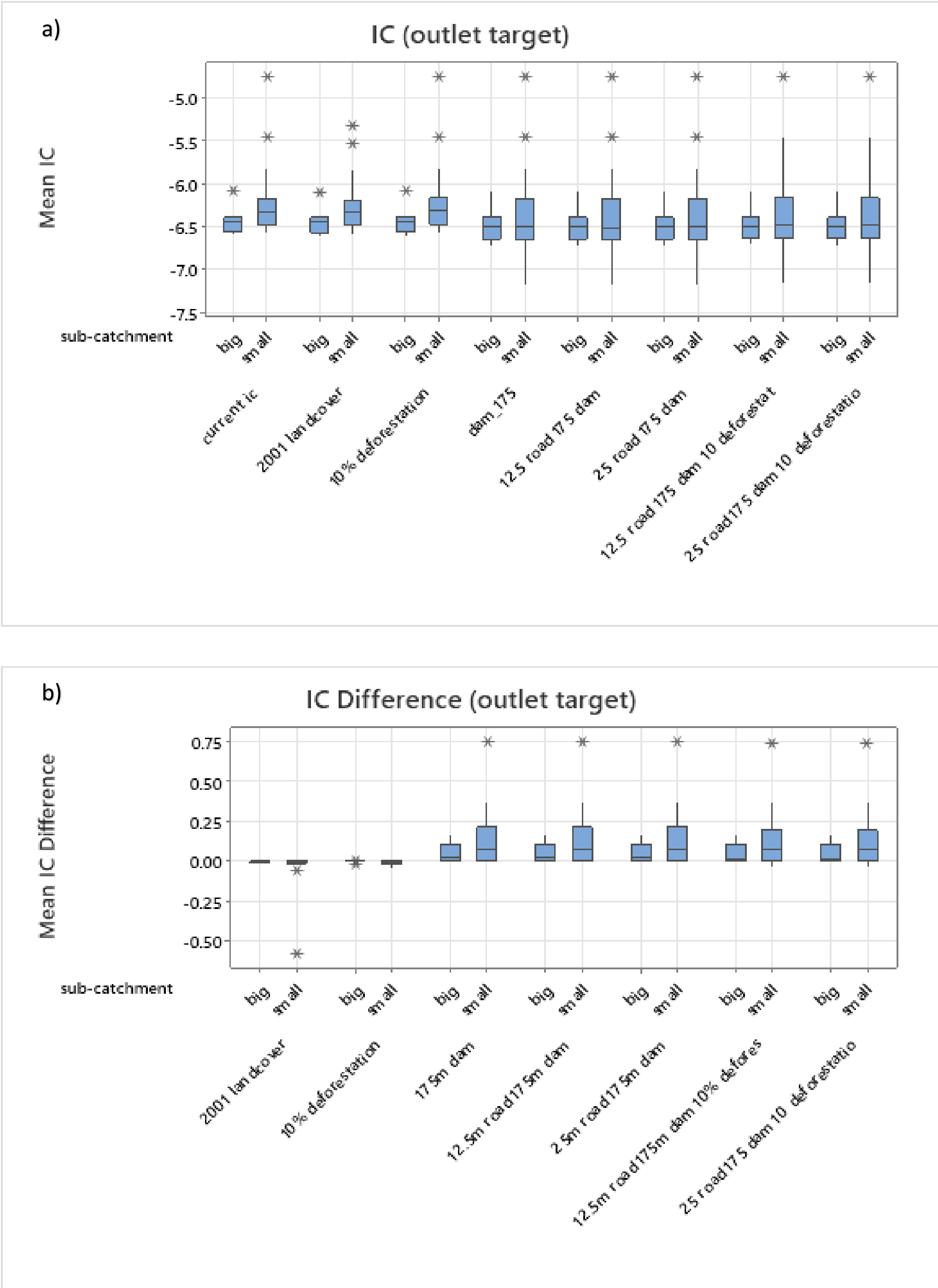

Figure 4.9 Boxplots of (a) mean IC values and (b) mean IC difference values.

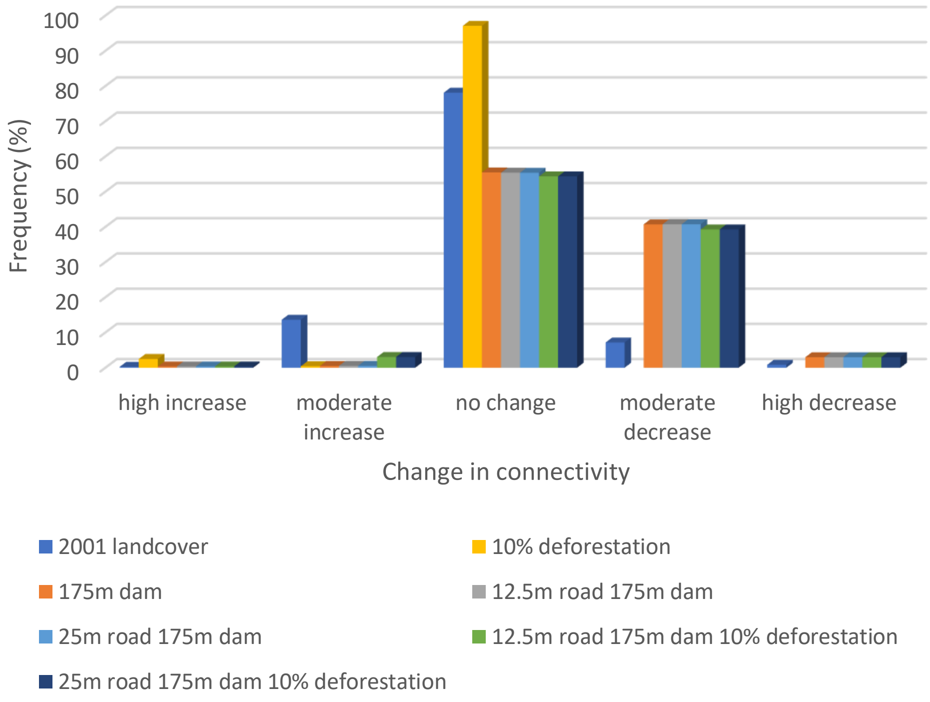

Figure 4.10 Change in connectivity between the outlet of the Baleh at the Rajang confluence and all upstream parts of the Baleh catchment. Values are frequency in percentage of modelled cells.

4.3.4. Impacts of Different Lake Levels on Connectivity in Upstream Sub-catchments (Scenarios 9-12)

When the river channel is used as the target (to understand lateral connectivity under normal circumstances/without the lake), the present and historical scenarios have a similar IC range of -4.6 to -5.8, with a $\bar{x}$ of -5.16 and a SD of 0.39. This shows that there has been no significant change in connectivity in the upper catchment over the past 2 decades. However, changes can be seen in certain areas of the catchment, e.g. some have experienced a Moderate Increase in IC (21%), and some a Moderate Decrease in IC (4%). Changes in IC reflect localised forest clearance and areas where native vegetation has been and continues to be disturbed (i.e. 3.5% decrease in forest, 62% increase in disturbed vegetation).

The dam will form a large lake whose area depends on lake level. The 87 m lake level inundates 180 km^2, while the 175 m lake level inundates 588 km^2 (Table 4.1). Model results suggest that these different lake levels will impact connectivity between hillslopes and the lake perimeter to different degrees. Connectivity is higher with the higher lake level (i.e. greater lake area) than it is with the lower lake level: the 87 m lake level has an IC range of -3.3 to – 5.9, with a $\bar{x}$ of -4.79 and a SD of 0.67, whereas the 175 m level has IC ranging from -2 to – 5.3, with a $\bar{x}$ of -3.95 and a SD of 0.84 (Figures 4.11 and 4.12). The results also show that smaller sub-catchments (i.e. those ranging in size from 20-250 km^2) have a higher IC than the larger sub-catchments (>250 km^2; Figure 4.12).

IC difference values also show that there is an apparent increase in IC when a lake is present (i.e. Scenarios 11 and 12) compared to the scenario with no lake (Scenario 9) (Figures 4.13 and 4.14). This can be seen in the 175 m dam scenario that has an increase in IC of approximately 70%, while the 87m dam scenario has an IC increase of approximately 60% (Figure 4.15).

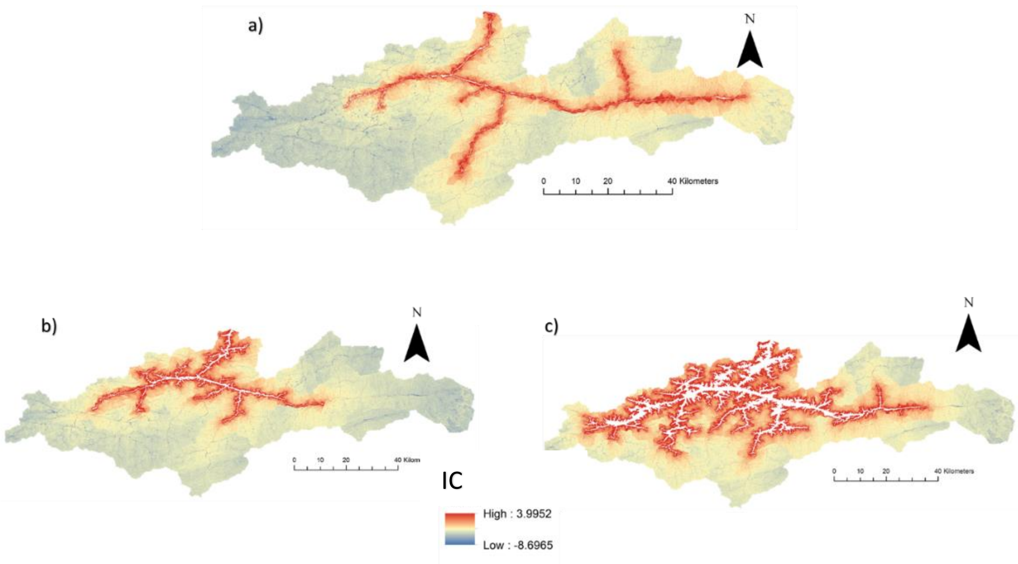

Figure 4.11 IC maps of (a) current scenario (no lake); (b) 87 m dam scenario; (c) 175 m dam scenario, with the river channel being used as target in (a), and lake levels of 87 m and 175 m

being used as targets in (b) and (c). Only catchment areas upstream from the dam are considered in this analysis.

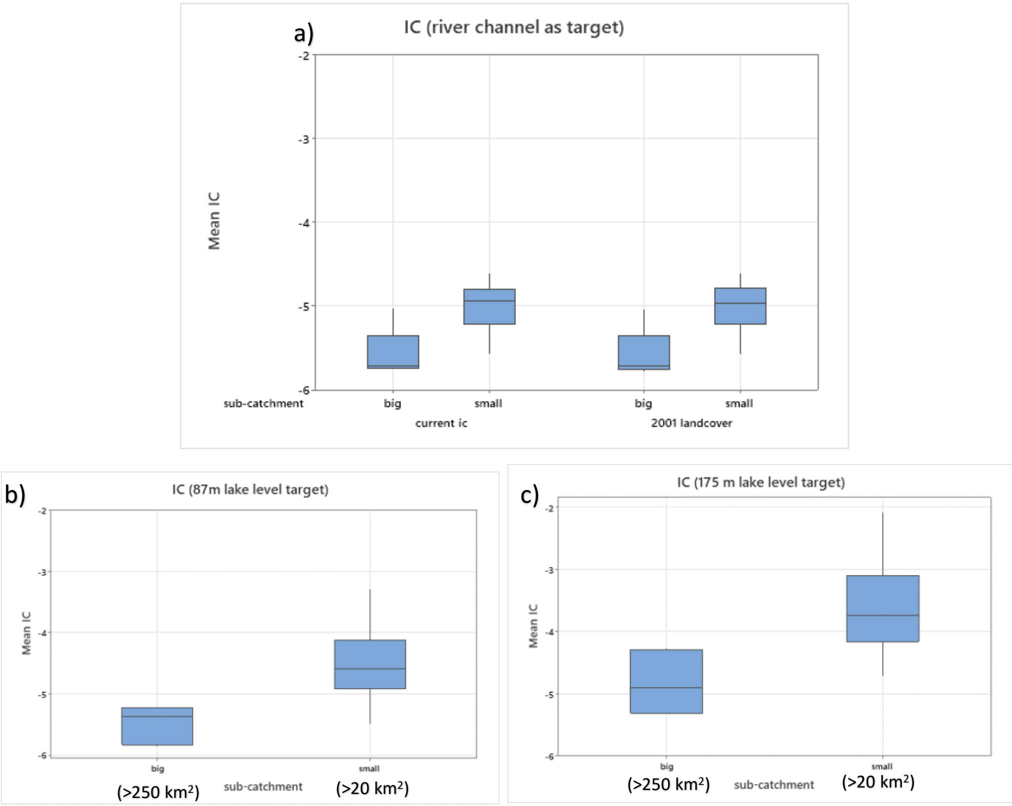

Figure 4.12 Boxplots showing the mean IC values of the (a) present and historical scenarios using the river channel as target, (b) 87 m and (c) 175 m dam scenarios using lake levels as targets.

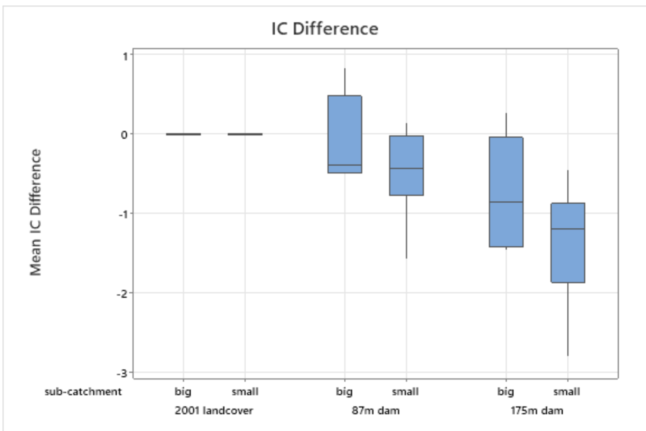

Figure 4.13 Boxplots showing the mean IC difference values of (i) current scenario minus historical scenario; (ii) current scenario minus 87 m dam scenario; (iii) current scenario minus 175 m dam scenario, with the river channel and lake levels being used as targets.

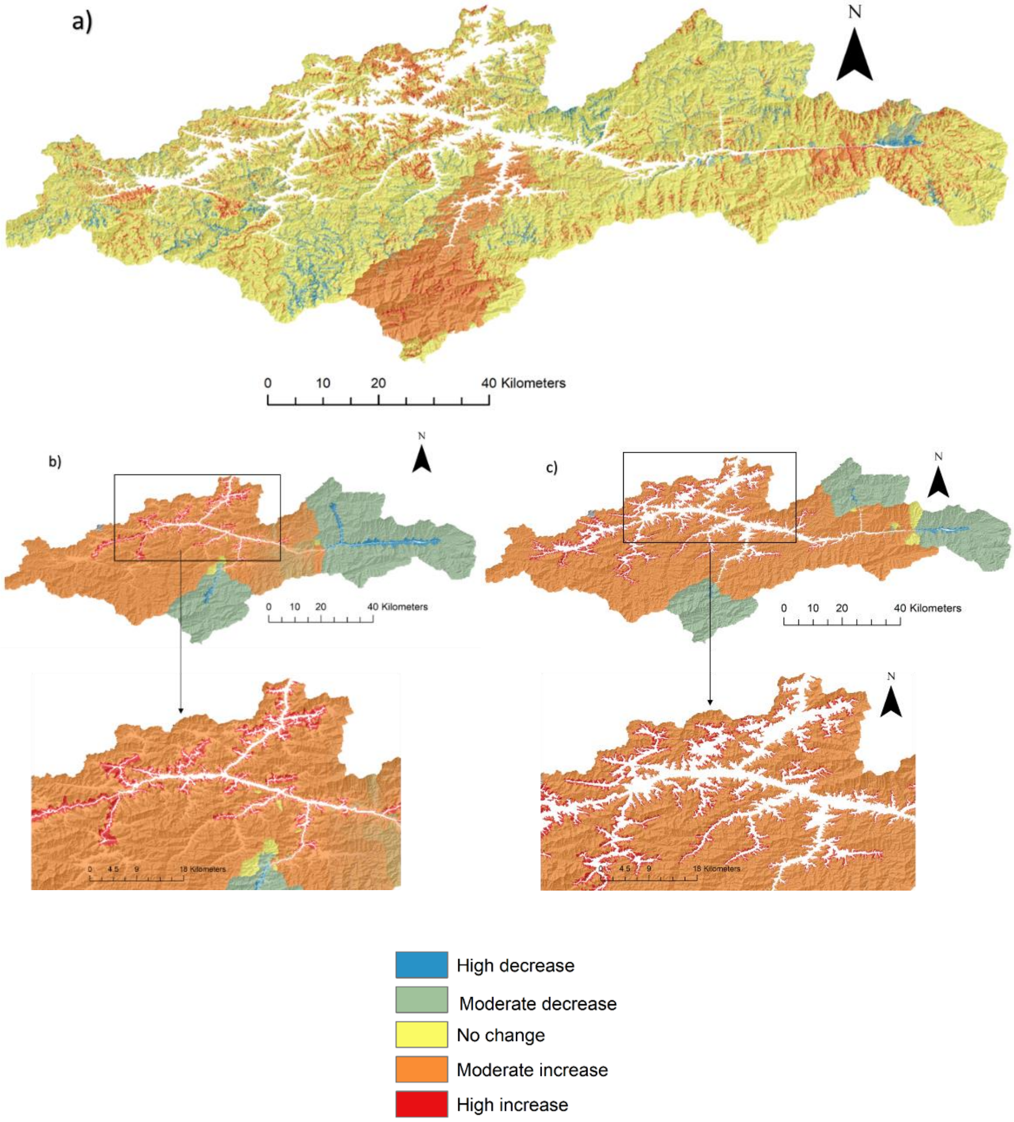

Figure 4.14 IC difference maps of (a) current scenario minus historical scenario; (b) current scenario minus 87 m dam scenario; (c) current scenario minus 175 m dam scenario, with the river channel and lake levels being used as targets. Only catchment areas upstream from the dam are taken into account in this analysis.

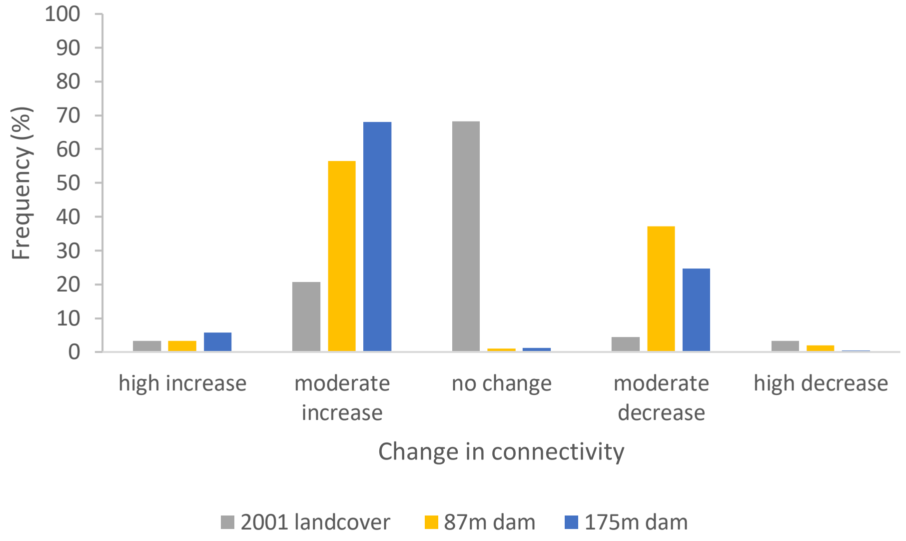

Figure 4.15 Bar chart of change in connectivity with the river channel and lake levels being the targets. Values are frequency in percentage of modelled cells.

4.4. Discussion and Conclusions

4.4.1. Main Findings

Work presented in this chapter suggests that historical changes in landcover have not altered connectivity between the Baleh and the Rajang to any great extent. This is largely because, to-date, most of the natural landcover remains intact, with relatively small and isolated areas of modified landcover. However, future roads and forest clearance of 10% are predicted to have detectable impacts on connectivity between the Baleh and the Rajang, leading to small decreases and increases in IC respectively. The IC models suggest that once the dam is built, its effects on connectivity will swamp those of the roads and anticipated landcover change. In effect, 44% of the Baleh catchment (i.e. the area upstream from the dam) will be disconnected from the Rajang. This has implications for sediment fluxes along this major river system. The work also suggests that operation of the dam will have implications for IC upstream of the dam because of how different lake levels/areas alter connectivity. Larger lake areas impact

IC most, and so managing water levels in ways to reduce changes in connectivity is possible. These results are discussed in more detail in the sections that follow.

4.4.2. Implications of Landcover Change and Road Construction for Catchment Scale Structural Connectivity

The IC models suggest that scenarios of future road construction and forest clearance across the Baleh catchment will reduce the ability of the landscape to obstruct water and soil, resulting in somewhat higher connectivity. This finding is consistent with Jautzy et al. (2021). The road connects the town of Kapit with the dam site and runs mostly along the northern side of the river close to and parallel with the river channel. Although the overall impact of this road on connectivity between the Baleh and the Rajang is limited (i.e. changes in mean and ranges of IC were very small), there were marked local effects similar to those reported by Llena et al. (2019). These authors found that roads artificially cut the drainage network, producing a localised increase in connectivity in the upslope area and a decrease in connectivity downslope; the morphological changes associated with road construction led to an increase of erosional activities uphill, triggering in some cases localised landslides. Their results also suggest that the sediment involved in the landslides now has a lower probability of reaching the target (i.e. outlet of the catchment) because of the effect of the road in trapping the material produced upslope. The similar changes in IC values for Baleh raise concerns that such local changes erosion and sediment transfer may follow completion of the road. Overall, our modelling supports Hypothesis 1 – that land use and cover change increase sediment connectivity, whereas road construction decreases connectivity in downslope areas.

The results also showed that the smaller sized sub-catchments have greater connectivity than the bigger ones as these sub-catchments are often characterised by steep terrain, high precipitation, and erodible soils, leading to higher rates of erosion and sediment transport. As a result, sediment loads in these sub-catchments can be several times higher than in larger, flatter sub-catchments.

4.4.3. Implications of Dam and Lake Levels on Sediment Connectivity

The presence of the dam – a major vertical element placed across the river channel – was predicted to affect connectivity to a much greater degree than either landcover changes or road construction. Thus, our results supported Hypothesis II - the dam has a marked effect on sediment connectivity, disconnecting the Rajang from large parts of the upper Baleh. While at a general level, this result is not surprising (there is a large literature showing how dams trap sediment, e.g. Gupta et al., 2012; Kondolf et al., 2014b), the use of IC to produce specific values of connectivity allowed for a quantitative and spatially explicitly comparison of the relative effects of these different infrastructural developments.

Interestingly, the results also showed signs of increasing connectivity downstream from the dam. This aligns with Poeppl et al. (2013) who reported low sediment connectivity (accompanied by fine riverbed sediment) in river sections upstream of active dams but high sediment connectivity (accompanied by a coarse riverbed sediment) downstream of dams in the Fugnitz and the Kaja river systems. Among many authors, Marchi et al. (2019) stressed how dams make the channel network less longitudinally connected than under natural conditions, and this implies a decreased efficiency of sediment transfer from the headwaters to downstream areas, and with longer times due to the decreased energy slopes. Just as our study focusses on structural connectivity especially on longitudinal connectivity and channel conveyance for the whole catchment, the study by Grill et al. (2015) also focusses on longitudinal connectivity based on the assumption of a direct and reciprocal relationship between fragmentation and connectivity. Their study shows that on a global basis, 48% of river volume is moderately to severely impacted by either flow regulation, fragmentation, or both. Assuming completion of all dams planned and under construction, Grill et al. (2015) suggested that this number would nearly double to 93%, largely due to major dam construction in Amazonian Basin. In Malaysia, there is a resurgence of interest in hydropower due to carbon commitments and this has implications for connectivity across the country if more and more dams are constructed.

Our results also confirm Hypothesis III – high water level in the reservoir increases connectivity in the sub-catchments where the lake is present compared to lower water levels. For this part of the work, projected flooded perimeters were used to represent connectivity targets to understand sediment dynamics upstream of the dam. The reason for simulating different lake levels was to understand if increasing water levels might lead to tipping point situations where the catchment suddenly lacked a decoupling feature and thus become more efficiently connected to the lake and, in turn, provided greater opportunity for sediment conveyance. Our results showed that at full lake level (i.e. 175 m), the reservoir and the hillslopes are more connected than at the much lower (i.e. 87 m) level. At full lake level, the dam impacts an appreciably larger area; doubling lake level (from 87 m to 175 m) increased the inundated area three-fold (from 180 km^2 to 588 km^2), making a much larger area "accessible" for sediment conveyance and potentially therefore sedimentation within the lake.

4.4.4. Implications for Hydromorphology, Stream Ecosystems and Management of the Baleh Catchment

This study is the first to assess structural connectivity in a tropical river basin. It is significant in being able to quantify the effects of various catchment changes that typically occur together but are rarely evaluated in ways that provide insights into how they interact.

Dams represent major barriers to the downstream (longitudinal) conveyance of sediment and nutrients, as well as to both the up- and downstream dispersal of aquatic organisms, potentially dramatically altering the connectivity of upstream sediment sources to downstream sinks and providing greater variation in the residence time in sinks (Ward and Stanford, 1995; Wohl, 2013; Rincón et al., 2017). The physical and ecological implications of reduced connectivity (e.g. channel geomorphology, community structure) have attracted increasing attention over recent decades. Lateral connectivity – that is between the channel and the wider landscape - is also important as it plays a significant role in catchment hydrological processes (Peter et al., 2017), including redistribution of soil and water (Kim and Mohanty, 2016), and alteration of sediment inputs to the channel network; changes in lateral connectivity may lead to channel widening, bed aggradation, and river scouring with implications downstream human settlements (Martini et al., 2019). Moreover, lateral connectivity has a direct effect on biological, chemical, and geomorphological processes in the root zone, affecting both abiotic (flow rate, temperature, oxygen concentrations, and water transparency) and biotic (species composition of plant and animal, food, and habitat availability, and species interactions; Yan et al., 2022).

The IC values provide a first order approximation of how lateral connectivity in the Baleh may be affected by anticipated rates of forest loss and the construction of an access road to the dam, with these alterations resulting in changes in connectivity between the Baleh and the Rajang. Reservoirs are recognised as impacting longitudinal connectivity, but less so lateral connectivity. IC indicated that for reservoirs, lateral connectivity is dependent on the water level (as well as the topography of the inundated area). With the Baleh dam in place, the lateral sediment connectivity will be significantly increased, especially when the lake is at full level. This inundated area will link stream channels, floodplains, and adjacent uplands (Burchsted et al., 2010) subsequently increasing the sediment supply from hillslopes. The extent of dam impacts on lateral connectivity will control, amongst other things, sediment, carbon and nutrient storage, extent of anaerobic metabolism and biogeochemical interfaces, nutrient fluxes, aquatic ecosystem productivity and biodiversity, riparian vegetation mosaics, and river channel pattern. Thus, the ability of dams to influence lateral sediment connectivity between the channel and floodplain is a key impact, and one from which many other hydrological, geomorphic, biogeochemical, and ecosystem impacts follow (Larsen et al., 2021).

Understanding the role of sediment source areas is vital to predict the sedimentological responses to anthropogenic disturbances such as road construction and forest clearance, and to help with catchment management. IC maps are useful in this regard, as they highlight areas that are well connected to the channel network, and which therefore may serve important roles in maintain catchment integrity. Because different targets can be chosen, it is possible to use the IC model to help identify source areas for points of interest and in this way assess how either disturbance of management might affect the linkages between the river channel and sediment source areas. Results from the model could also be used in conjunction with other tools or approaches to fully evaluate the effects of dams. In the next chapter (Chapter 5), the effects of modified flows on sediment entrainment within the Baleh are modelled, and these results are later integrated with those from the catchment connectivity analysis to provide a more holistic picture of how the dam is likely to impact the Baleh fluvial system (Chapter 6).

Sediments accumulate within the reservoir and may substantially reduce its the life span, causing major impacts on either HEP revenue or storage capacity. Due to sedimentation, many large reservoirs in the US that had originally been designed for up to 200 years experienced a reduction in lifetime by 50-100 years (Hargrove et al., 2010). Therefore, additional costs are associated with dredging the reservoir and removing sediments. Land use changes upstream from Baleh dam will need to be minimised in order to reduce sediment loss, especially bearing in mind that climate change may result in increased rainfall magnitudes and intensity (Waters et al., 2003; Peck et al., 2012).

The International Hydropower Association (IHA) launched a knowledge hub on successful sediment management to extend the lifetime of reservoirs in December 2017 to raise awareness for the need to manage sediment in reservoirs (IHA, 2017). Different options exist to tackle and avoid reservoir siltation: 1) reduction of sediment input including the decrease of upstream soil and channel erosion, and sediment trapping upstream of the reservoir (precautionary action), 2) passing sediment around or through the reservoir by maintaining sediment transport and reducing its deposition (attendant action), and 3) excavating sediments or flushing sediments by adopting dam operation (correcting action) (Kondolf et al., 2014a). These actions require specific knowledge on and data for quantifying the processes that influence sediment entrapment. Planning and environmental impact of reservoirs needs to consider connectivity, set within a context of land use and climate change impacts on a catchment scale (Zarfl and Lucía, 2018) more fully. The work presented in this chapter suggests that land use change in the Baleh may not greatly affect connectivity, but modelling was based on the assumption of a 1% annual decrease integrated over 10 years (i.e. 10% change in total). Some areas of Malaysia are experiencing much greater rates of forest loss than modelled for the Baleh (Abdullah and Hezri, 2008; Hansen et al., 2013). Even at 1%, impacts may be much greater than reported here when considered over longer timescales, especially bearing in mind the long (100-year +) operational life of the dam.

While structural connectivity (i.e. IC) is used in this chapter as an explanatory or predictive tool, it is important that these indices are interpretable in relation to geomorphic processes, material properties, and forcing styles and magnitude-frequency spectra. Therefore, as part of future work, it may be possible to integrate this IC modelling results with sediment source inventories of the Baleh to produce a sediment management plan for the catchment so that the IC represents a valuable tool for ranking intervention measures and management strategies at the catchment scale.

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CHAPTER 5

Functional Flows:
An Environmental Flow Regime for the Riverbed Dynamics & Habitat Formation of a Large Tropical River

5. FUNCTIONAL FLOWS: AN ENVIRONMENTAL FLOW REGIME FOR THE RIVERBED DYNAMICS AND HABITAT FORMATION OF A LARGE TROPICAL RIVER

ABSTRACT

This chapter uses a number of different models to evaluate the implications of the range of different flow magnitudes on sediment entrainment and habitat heterogeneity. Some of the flows simulated were natural high flow events, while others were hydropower releases using 3, 4 and 5 turbines. The simulations suggested that, on their own, hydropower releases would not lead to the extent of sediment entrainment that characterises the natural flow regime. However, when the catchment is wet, and tributaries downstream from the dam are discharging relatively high flows, sediment entrainment equivalent to small to moderate natural events was predicted to occur. The coefficient of variation (CV) in velocity was used as an index of hydraulic habitat heterogeneity. Analysis of CV at each of the sites across the flow range indicated that relatively high heterogeneity occurs at low flows. A number of flow recommendations for minimum releases from the dam are made based around monthly natural baseflow values. Analyses of these recommended low flows suggest that they will provide high levels of hydraulic heterogeneity as well as the exposure of gravel bars as happens naturally in the unregulated river. The chapter represents a novel example of development of flow recommendations for a tropical river based around maintaining fluvial processes and characteristics.

5.1. INTRODUCTION

Rivers in the world's tropical regions are characterised by marked hydrological fluctuations across a variety of temporal scales, from low discharges during dry seasons (even including droughts) to flash floods in rainy or monsoonal periods (Syvitski et al., 2014). However, many tropical rivers are heavily regulated by dams whose operational regimes alter these natural patterns of variability (Greathouse et al., 2006; Chong et al., 2021a). Tropical catchments currently host over 3,500 large dams used for water storage, hydropower production, irrigation, navigation, or flood control and changing water demands in the future are likely to increase the need for flow regulation, especially in rapidly developing tropical countries where energy demand is increasing.

Dams alter discharge magnitudes, timings and frequencies, and consequently affect downstream morpho-sedimentary dynamics (Ligon et al., 1995; Morris et al., 2008; Poff and Schmidt, 2016). The morpho- and hydro-sedimentary responses to regulation differ greatly between rivers, depending on the location, the substrate, the amount, and temporal distribution of water, and sediment supply (Brandt, 2000). Tropical rivers are distinct from those of other climate regions in a number of ways (Chong et al., 2021a) and ecologically important and unique due to high level of endemism and species richness (Ramírez et al., 2008); they support diverse assemblages of plants and animals, including many species that remain to be described. Many tropical species have unique adaptations to specific habitats, microhabitats, or food sources, while others are more ubiquitous and capable of living in a wide range of conditions (Dudgeon, D., 2000; Scremin-Dias, 2009; Val and de Oliveira, 2021). Thus, the study of the effects of flow regulation on these systems is crucial, both to understand the functioning of these important but fragile environments and for species conservation purposes.

When discharge exceeds the critical threshold to entrain riverbed materials, bedload transport occurs. This process involves the entrainment, movement, and redistribution of sediments, resulting in patchy areas of scour and deposition that determine riverbed sedimentary and morphological characteristics (Schwendel et al., 2010). Flow regulation changes the magnitude and frequency of floods and so alters the transfer of sediment downstream. These changes alter the dynamics and morphology of the fluvial system resulting in, among other things, bed incision, armouring, and loss of active sedimentary areas (e.g. Vericat et al., 2006; Hassan & Zimmermann, 2012).

Managing ecological water allocations - including the quantity, timing, frequency, duration, and quality of river flows for freshwater ecosystems, herein referred to as 'environmental flows' - is increasingly being required to sustain an agreed-upon level of ecological condition and provide sufficient water for societal needs (Petts, 1996; Tharme, 2003; Newson and Large, 2006; Richter et al.,2006; Poff et al., 2010). Geomorphology occupies a key realm in this arena because it is the science that focusses on understanding the process-based interactions between river flow, sediment, morphology, and organic materials that shape the type, quality, and availability of habitat use across space and time (Poff and Ward, 1990; Thoms and Parsons, 2002; Jacobson and Galat, 2006; Tracy-Smith et al., 2012).Thus, the study of geomorphic processes should be central to environmental flows (e-flows). However, as outlined in Chapter 2, relatively few studies of the impact of dams on sediment transport have been undertaken in topical rivers, and hardly any have used an understanding of transport processes to help set environmental flows targeted at maintaining fluvial dynamics.

Periodic low flows are also important ecologically because they either create suitable conditions for specific life stages or facilitate access to suitable habitat. For instance, low flows create slow flowing or standing water (backwater) areas away from the main wetted channel that may be important nursery grounds for young fish, while low water stages expose gravel bars that may be important habitats for certain invertebrates or breeding birds (Dewson et al., 2007; Bradford and Heinonen, 2008). Thus, lower flows may promote a patchy mosaic of different habitats that create heterogeneity within river reaches; conversely higher flows wet the whole channel and 'drown-out' hydraulic differences between e.g. riffles and pools. The role of habitat heterogeneity (HH) in promoting species diversity is one of the most often cited concepts in ecology science (Ricklefs and Schluter, 1993). HH seems more tractable than many other factors believed to support or enhance biodiversity (e.g. productivity, disturbance regime; Bell et al., 1997; Palmer et al., 1997). Furthermore, arguments that species diversity may contribute to community stability and ecosystem function have increased the focus on habitat heterogeneity in the restoration context (Tilman, 1996).

The foregoing discussion suggests that maintaining (i) habitat forming high flows along with (ii) an understanding of how low flows influence exposure of gravels bars may increase habitat heterogeneity by creating low flows areas, are two key considerations, especially when empirical information on species habitat requirements is insufficient to allow application of species-based habitat modelling (Wohl et al. 2015). Despite extensive searching for published material and consultation with experts and field biologists, more or less no data or information exist on species present in the Baleh that could be used to provide the biological input needed to run models such as PHABSIM. This chapter therefore focusses on identifying aspects of the flow regime of the Baleh that are important for habitat formation and heterogeneity, the latter including flow hydraulics and maintaining exposed areas, and so can be considered functional flows (sensu Escobar-Arias and Pasternack, 2010). The objectives are to (i) understand the effects of a range of natural and anticipated dam operational flows on sediment entrainment; (ii) understand how flow magnitude and water stage affect hydraulic habitat heterogeneity; (iii) assess the timing and frequency of important low and high flows; and (iv) integrate Objectives i-iii to provide recommendations for a functional flow regime to maintain habitat formation and heterogeneity.

5.2. METHODS

5.2.1. STUDY SITES

Background details on geology, climatology and hydrology of the Baleh River are provided in Chapter 3, which has been published as a paper (A framework for Hydrological characterisation to support Functional Flows (HyFFlow): Application to a tropical river). Three study reaches are selected for the purpose of this chapter (Table 5.1; Figure 5.1 and Plate 5.1). Each reach is approximately 800 m in length. These wadable reaches are chosen due to their accessibility so that data could be collected without always relying on boats. They are also at increasing distances downstream from the dam, allowing us to make recommendations based on an extensive section of river where flow accretion occurs due to tributary and other inputs. The reaches are geomorphically heterogeneous (i.e. riffles and pools, gravel bars at low flows) and two of them extend up and downstream from confluences.

Table 5.1 Coordinates of the selected sites.

Site	Coordinates (lat, long)	Width (m)	Distance from dam (km)
1	1.8101, 113.7564	183	1.85
2	1.8519, 113.5778	213	22
3	1.8913, 113.4345	280	40

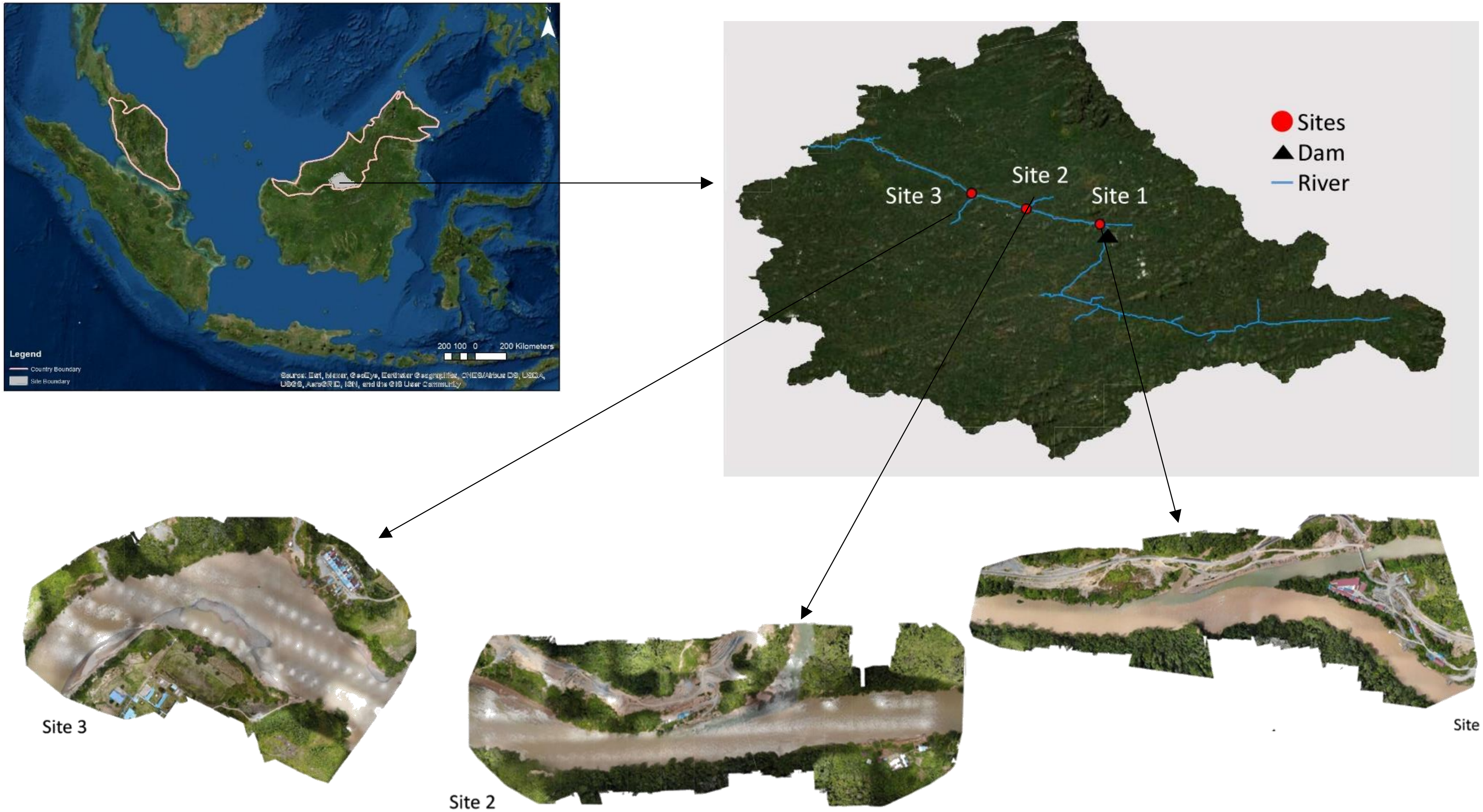


Figure 5.1 Location map of the study area, sites, and orthomosaics of each site.

Plate 5.1 Photograph of Sites 1, 2 (upper left and right respectively) and 3 (lower).

5.2.2. Topographic and Hydraulic Surveys – UAV and ADCP (Field Methods)

To characterise the geomorphology of the study sites, field measurement was combined with UAV photogrammetry for mapping. Aerial imageries were collected using a DJI MAVIC 2 Enterprise Dual UAV flying over an altitude of 150 m for Baleh that is approximately 120 m wide. This resulted in a continuous 0.1 m Digital Elevation Model (DEM) with corresponding high-resolution orthophotos created from these images using Structure-from-Motion (SfM) photogrammetry.

The ground control points (GCPs) used for photo and model rectification in SfM were established and surveyed prior to the UAV flight. GCPs were placed along both sides of the channel at intervals of 0.2-0.3 km. The control points' geographic coordinates were collected using a Geomax Zenith 35Pro RTK GPS (Hz 3 mm ± 0.5 ppm, V 5 mm ± 0.5 ppm). However, the imagery did not capture bed elevation data for the channel's submerged bed areas due to extreme turbidity and tall riparian trees which shaded the banks to a distance up to circa 5 m into the channel in places.

To obtain bed elevations for the wetted areas, the water surface elevation was extracted from the point cloud from the SfM-produced orthophotos produced using Pix4DMapper software. Then, for each survey point across the site, the water depth value was extracted from the RiverRay Acoustic Doppler Current Profiler (ADCP) and subtracted from the water surface elevation to give bed elevation. Note that as the ADCP did not have a GPS, a handheld Garmin GPS Map 66s with an accuracy of ±3 m was used to geolocate the points.

The 0.1 m pixel-resolution DEM was then used in the Hydrologic Engineering Centre River Analysis System (HEC-RAS®) 6.1 for 2D hydraulic modelling. The models simulated hydraulic conditions at discharges of interest (refer to Section 5.2.5 for more details) and were combined with field data on sediment grain-size distributions (GSDs) to estimate critical entrainment thresholds for representative grain sizes at each of the three sites.

5.2.3. Field Measurement of Flow Hydraulics and Grain Size Distributions

Fieldwork was conducted on the 9th – 14th of March 2022. This was at the beginning of the low flow season, so extensive areas of the channel were either exposed or very shallow. This helped to reduce areas where bed elevations had to be estimated (as described above) and allowed easy access for using the ADCP handheld. Cross-sectional transects are established at the up and downstream ends of each site, from which bed elevations, water depths, velocities and discharges were obtained using the ADCP. These data were used to assign boundary conditions for HEC-RAS® model validation.

Sediment grain-sizes were measured using the Wolman Pebble Count method (Wolman, 1954). Flows were low during field surveys and so it was possible to measure clasts from exposed gravel bars and shallow wetted areas at each site. For each site, 200 individual clasts were picked from the bed and their intermediate b-axis is measured to the nearest mm; clasts were obtained along transects that criss-crossed exposed and/or wadable parts of each site and chosen beneath the tip of the toe without looking down.

5.2.4. Construction of Hydraulic Models

Due to the comprehensive set of features and capabilities specifically designed for hydraulic modelling, HEC-RAS® was chosen as the preferred software for hydraulic modelling. It offers a user-friendly interface, making it accessible to both experienced professionals and beginners in hydraulic modelling and provides detailed documentation and tutorials, facilitating the learning process and ensuring efficient utilisation of the software. Additionally, HEC-RAS® has a strong support community, with a wide range of resources available online, including forums, user groups, and technical support. This ensures that users can access assistance and guidance when encountering challenges during the modelling process.

HEC-RAS® 2D was set up using respective site DEMs (refer to 5.2.2 for details) to accurately capture surface topography and flow paths. For each site, a computational grid composed of around 20,000 rectangular and irregular (greater than four faces/sides) cells of a nominal size of 3 m was generated to capture variability of the underlying terrain for the 2D sediment simulation (Figure 5.2).

Manning's roughness coefficients for the sites were defined based on land cover derived from Lum (unpublished MRes thesis). The upstream boundary conditions for the modelling domain for each site were input from the types of events selected (refer to 5.2.5 for details). Normal Depth was chosen as the downstream boundary condition, where the downstream friction slope was given.

The HEC-RAS® 2D model was used for the simulations as 2D is more accurate and easier to use because the flow path of the water is not fully known, and it only requires a terrain model (i.e. DTM). Another reason being is the velocity, momentum, and the direction of the flow are more accurately accounted for in 2D model. HEC-RAS® 2D using unsteady flow model and Diffusion Wave equations with a 1-second computational interval was applied to simulate all the scenarios. The HEC-RAS® 2D hydrodynamic simulation output was exported in 1-min output intervals. The HEC-RAS® 2D was validated against the hydraulic data collected in Section 5.2.3. The validation process involved comparing the model outputs to the field data, focusing on the corresponding depth and velocity measurements obtained during the field trip. The agreement between the modelled results and the field data was assessed using established metrics and criteria. The error metrics of the hydraulic models are presented in Table 5.2 and Figure 5.3.

The error metrics in Table 5.2 show that the hydraulic models have acceptable accuracy in predicting the depths and velocities of each site as the R-squared shown are approximately 0.6 - 0.8. These values indicate a relatively strong correlation between the predicted and observed values, suggesting that the model captures a substantial portion of the variation in the depth and velocity data. Error metrics also show that Site 1 has the best depth and velocity predicted values (RMSE and MAE ranging from 0.3 m - 0.9 m); whereas Sites 2 and 3 have relatively higher RMSE and MAE in the prediction of depth that is approximately 1 m.

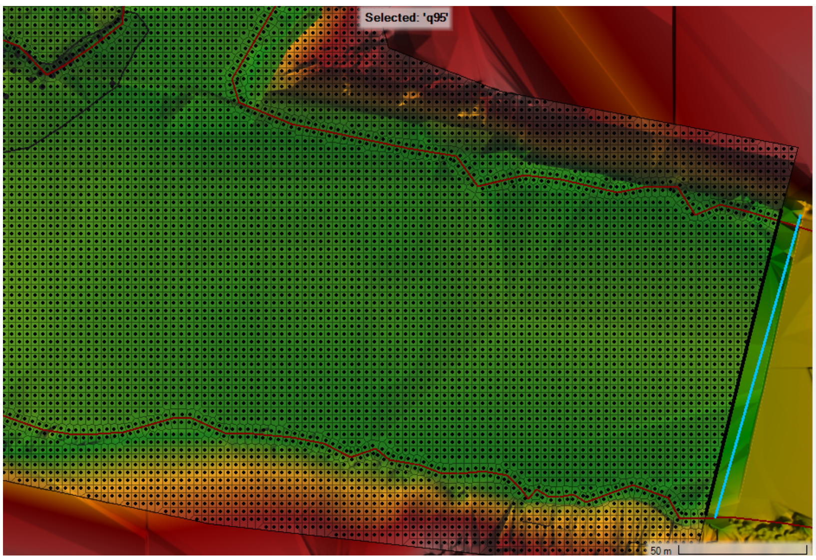


Figure 5.2 A snapshot of the computational grids for the 2D HEC-RAS® simulation**.**

Table 5.2 Error metrics of the model for each site.

Site and Metric	***R^2***	***Root mean squared error (RMSE) (m)***	***Mean Absolute Error (MAE) (m)***
Site 1 Depth	0.81	0.96	0.85
Site 1 Velocity	0.62	0.37	0.30
Site 2 Depth	0.67	1.43	0.94
Site 2 Velocity	0.70	0.47	0.37
Site 3 Depth	0.62	1.09	0.90
Site 3 Velocity	0.81	0.66	0.54

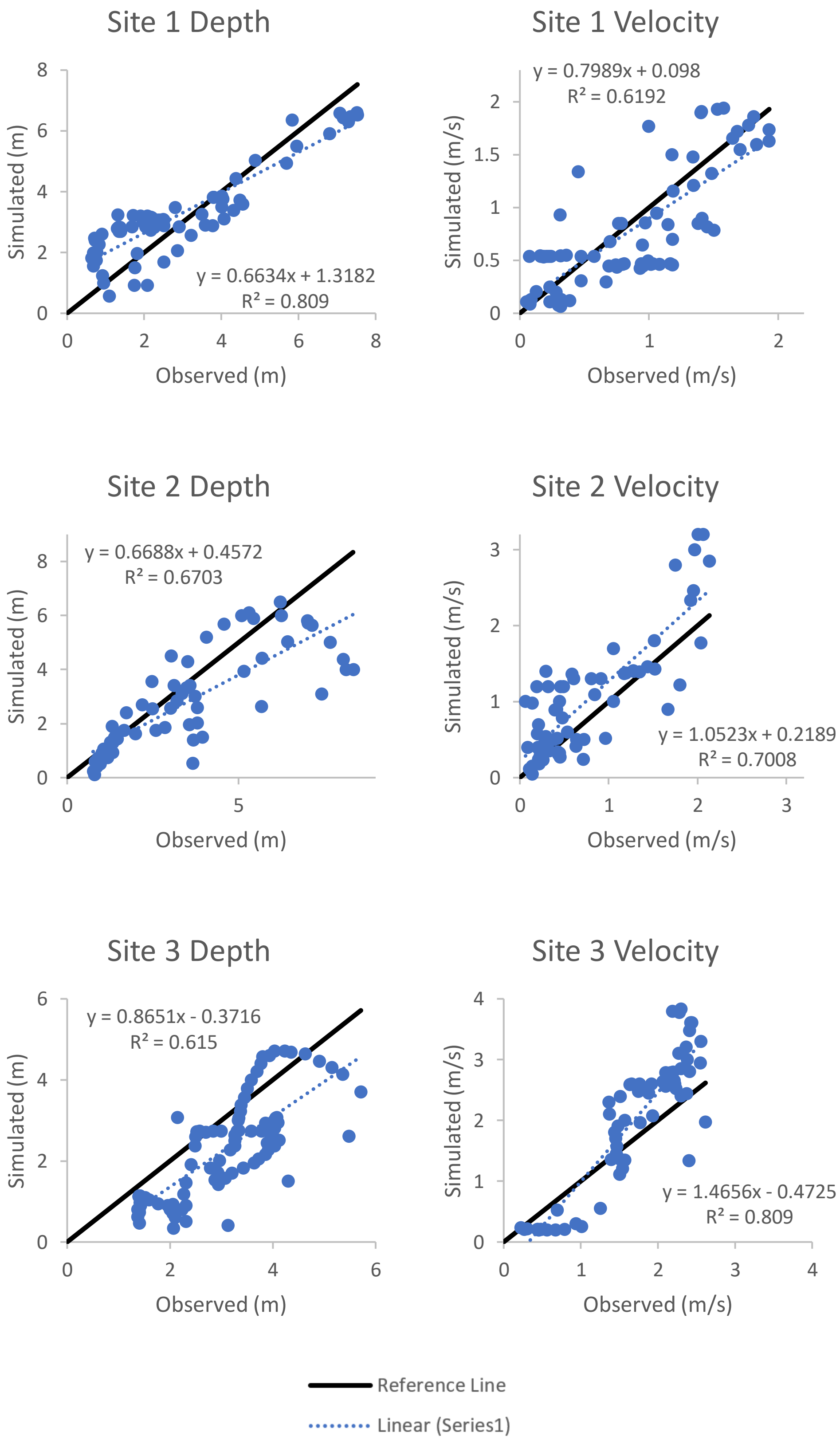


Figure 5.3 Model quality assessments.

5.2.5. Simulations - Detail Choice of Flows and Indicative Grain Sizes

5.2.5.1. Choice of Flows

The insights into the hydrological regime of the Baleh provided by HyFFlow (Chong et al., 2021b) are important as they provide a starting point development of functional flows. HyFFlow identified several types of high flow event and their timings, as well as all the IHA metrics related to low flow magnitude, timing duration and frequency. The current chapter focuses on understanding the functional roles of each of the main event types identified, along with the effects of the likely HEP operational regimes (how they influence scour, sediment transport and associated changes in habitat and the effects of low flows on hydraulic habitat and heterogeneity).

For the entrainment analysis, the 3 main event types in Baleh are simulated (i.e. Types A, B and C identified in HyFFlow); as detailed in Chong et al. (2021b), the other event 'types' were single events that did not classify into the main types and so are not analysed here. For each type, the effects of 5 events were simulated, to cover the full range of magnitudes that characterised each type, i.e. very small, small, moderate, large, and very large events in each type. In addition, effects of dam releases from different numbers of turbines were modelled. There are five turbines, each releasing 124 m^3/s. For sediment entrainment, the effects of 3, 4 and 5 were turbines modelled.

In addition, the Q95 was also simulated. This flow percentile has historically been used in many rivers as the minimum maintained or minimum acceptable flows for many dammed rivers (e.g. Gibbins and Acornley, 1998). SEB proposed to adopt an "environmental flow" (250 m^3/s) during the dam filling stage, so it was also simulated to assess its implications for the river. With this and other low flows, the focus was on hydraulic heterogeneity and gravel exposure. A range of lows flows and extending up to higher ones were simulated for each site and their velocities were extracted from all cells of the HEC-RAS® model. Coefficient of variation (CV) of velocities has been demonstrated to sufficiently represent the hydro-morphological heterogeneity (e.g. Gostner et al., 2013) and so was used as the metric of heterogeneity. The exposure of the gravel bars was also studied by evaluating the extent to which key low flow values exposed gravel areas. The focus of this analysis was at Site 3 as the site had gravel bars exposed at low flows. Field observation of this and other locations further downstream showed that certain regularly occurring low flows expose lateral and mid channel bars; hence the focus of this part of the work was to establish flow levels that cause exposure.

These analyses resulted in a total of 12 simulations for each site (Table 5.3). Note that site specific discharges were used in all modelling. Thus, for the high flow accretion ratios based on catchment area were used to translate a hydropower release at the dam site (Site 1) to discharges at Sites 2 and 3; for the low flow analysis, respective site flow percentiles were used to simulate hydraulic conditions at site natural low flows.

The HEP releases of four and five turbines produce a discharge that translates to approximately the dam site's Q40. The estimates of flow accretion downstream from here implicitly assume that the patterns of rainfall in all downstream sub-catchments are such that tributaries are flowing at approximately their respective Q40, and so are contributing flow that scales to their catchment areas. This may not always be the case, e.g. when the catchment is wet, tributaries may be delivering flows greater than their respective Q40 and hence not correlated with the HEP. Thus, when the catchment is wet, flows in the downstream river may exceed the simple area-based ration applied to the HEP releases and so sediment entrainment may be greater. To address this, another set of simulations were run, with flow accretion based on higher flows in the tributaries (Q10). This was all done using SWAT® and produced a higher set of discharges for the study sites. The entrainment at these discharges was then modelled.

5.2.5.2. Entrainment

With the construction of hydraulic models (HEC-RAS®) as mentioned in Section 5.2.4, shear stress values can be extracted from the modelling output. For entrainment to occur, shear stress must exceed the critical shear stress for a given sediment size (i.e. $D_{i\text{-}s}\tau > \tau_{c\text{-}Di\text{-}s}$), where $\tau_{c\text{-}Di\text{-}s}$ is the critical shear stress (N/m^2) needed to entrain a particle, and $D_{i\text{-}s}\tau$ is the bed shear stress (N/m^2). The dimensionless critical shear stress or the critical Shields parameter is denoted as

$$\tau_{*c} = \frac{\tau_c}{(\Upsilon_s - \Upsilon)D} \quad (1)$$

where τ*c is the critical Shields parameter/dimensionless critical shear stress, ϒs= specific weight of sediment, ϒ= specific weight of water, D= diameter of sediment, τc = critical shear stress.

The hiding effect describes how fine sediments surrounded by larger material are protected from flow forces. The hiding effect has been identified as the main cause of the lack of motion of particles under shear stresses above the theoretical value for their entrainment (Vericat et al., 2008; Church, 2010) Hiding can be quantified and used as a multiplier to help produce a more robust estimate of the shear stress needed to entrain a given sediment percentile (i.e. given the size of the surrounding sediment sizes, what shear is needed to entrain a given sediment). The hiding function (εi-s) was estimated following the White and Day (1982) formulae:

$$\varepsilon_{i\text{-}s} = [0.4\ (D_i/D_u)^{-0.5} + 0.6] \quad (2)$$

and

$$D_u = 1.6D_{50\text{-}s}\ (D_{84\text{-}s}/D_{16\text{-}s})^{-0.28} \quad (3)$$

where $D_{i\text{-}s}$ is the size of a surface particle i (in m), and $D_{16\text{-}s}$, $D_{50\text{-}s}$ and $D_{84\text{-}s}$ are the respective percentiles (m) in the surface GSD. This hiding function was used as a multiplier for the critical shear stress. As previously indicated by Sutherland (1992), it either reduces or increases the critical shear stress.

Table 5.3 Key flow percentile for the study sites under the natural flow regime (historical data record) and flow magnitudes, and associated percentile of each of the simulated flows.

Natural Condition	**Site 1 (m^3/s)**	**Site 2 (m^3/s)**	**Site 3 (m^3/s)**
Flow exceeded 5% of the time (Q5)	1375	1801	2338
Flow exceeded 50% of the time (Q50)	514	673	873
Flow exceeded 90% of the time (Q90)	219	287	372
Flow exceeded 95% of the time (Q95)	172	225	292

Discharge magnitude (m^3/s)				
Scenario	**Site 1**	**Site 2**	**Site 3**	**Equivalent Flow Percentile**
1 turbine	124	162	205	**Q99**
2 turbines	248	325	410	**Q86**
Environmental Flows	250	328	413	**Q86**
3 turbines	372	487	615	**Q70**
4 turbines	496	650	820	**Q54**
5 turbines	620	812	1025	**Q40**
Type A_very low	463	606	787	**Q56**
Type A_low	835	1094	1420	**Q22**
Type A_typical	1069	1400	1818	**Q12**
Type A_high	1244	1630	2115	**Q7**
Type A_very high	1537	2014	2614	**Q3**
Type B_very low	1347	1764	2290	**Q5**
Type B_low	1707	2237	2903	**Q2**
Type B_typical	1993	2612	3390	**Q0.7**
Type B_high	2260	2960	3843	**Q0.3**
Type B_very high	2683	3515	4563	**Q0.1**
Type C_very low	1340	1756	2279	**Q5**
Type C_low	1966	2576	3344	**Q0.8**
Type C_typical	2194	2875	3731	**Q0.4**
Type C_high	2338	3063	3976	**Q0.2**
Type C_very high	2819	3693	4794	**Q0.05**

5.2.6. HYDROLOGICAL MODELLING WITH SWAT

The Soil and Water Assessment Tool (SWAT® or ArcSWAT®) was used to predict and understand the likely impoundment effect on frequency of competent events under different rainfall and runoff magnitudes. ArcSWAT® was chosen for this specific task due to several factors. First, it is widely used and has proven capable of simulating flows in a range of hydro-climatological settings. It has a user-friendly interface that simplifies the model setup and calibration processes; other similar models are for example, dependent on the use of R and so are much less easy to implement. Furthermore, its integration with the ArcGIS platform allows for seamless data management, spatial analysis, and visualisation, which are essential for our project's focus on watershed-scale hydrological processes.

The model was used to simulate three recent years (i.e. 2014, 2015 and 2017 representing dry, typical and wet years) with their respective rainfall data obtained from the Department of Irrigation and Drainage Malaysia (refer to Chapter 3 for more information); simulations show how different dam releases translate to different flow magnitudes depending on prevailing runoff, and what the implications are for actual flow peaks (and in turn, entrainment) as a function of the combination of HEP flow and dam overspill. As the focus is on understanding sediment entrainment, the HEP plant operating on 5 turbines (i.e. generating the highest shear stress) was chosen for these simulations.

The model divides the main river catchment into smaller sub-catchments which represent hydrologic response units based on land use, vegetation, soil, and slope characteristics (Figure 5.4). SWAT® requires several types of input data, such as land use, temperature, topography, and precipitation, to quantify the water balance of a watershed. The hydrological simulation has two components, the land phase and routing phase. The land phase of the model controls the amount of water, sediment and nutrient loadings in each sub-basin delivered to the main channel. The routing phase is the movement of water, sediment, and nutrient through the channel network of the catchment to each basin outlet. ArcSWAT® (Arnold et al., 1998) is selected for the present study as it is a user-friendly plug-in that works within the ArcGIS suite.

A Digital Elevation Model (DEM) is obtained from the NASA Shuttle Radar Topography Mission (SRTM) with a resolution of 30 m per pixel, which matches the Landsat imagery. This is used in ArcSWAT® for delineating the watershed and sub-watersheds. Slope values are automatically generated in ArcSWAT® with the DEM. A local soil map produced by the Department of Agriculture Sarawak in 1968 was used for modelling. This was compared against the FAO-UNESCO Soil Map of the World (SMW). The local soil map has three soil classes while SMW only has one soil class for the Baleh catchment. The soil classes of both maps generally matched for the rest of Sarawak so the soil classes and properties from SMW that match the local soil map were extracted and used for the modelling. Outputs from the supervised classification component were used as land use maps.

The NCEP Climate Forecast System Reanalysis (CFSR) available on the SWAT®'s official website was used to obtain the daily minimum and maximum temperature, relative humidity, wind speed and solar radiation, all required by the model. CFSR is a high resolution, global, coupled atmosphere-ocean-land surface-sea ice system generated from meteorological model reanalysis, which is a combination of field and surface observations, a meteorological model, and remote sensing data. It has been tested and applied in tropical watershed models successfully (Lauri et al., 2014; Tan et al., 2017; Duan et al., 2019).

SWAT® allows a dam to be built in the model, such that the effects of the dam on the downstream flow regime can be simulated. The required dam parameters include its location, dam height and water surface areas associated with different spillway volumes. The key hydrological components relate to the water balance equation which incorporates water inputs and outputs. The reservoir inflow includes loadings from all upstream subbasins, while outflows require information on dam operation. These engineering and operational characteristics of the dam were provided by Sarawak Energy Berhad (Lum, unpublished MRes thesis).

Daily flows below the dam were simulated for each of the example years based on their rainfall and associated runoff, with hydrographs produced to look at high flow magnitudes and frequencies in the downstream river.

Figure 5.4 Baleh sub-catchments labelled with number codes, divided using SWAT® modelling.

5.3. Results

5.3.1. GSD and Sediment Entrainment at High Flows

The grain size distributions (GSDs) measured in the field and critical shear stress values for each site are shown in Figure 5.5 and Table 5.4 respectively. Based on the median bed-material particle size (D_{50}) extracted from each site, it shows that all sites are within the range of a gravel-bed river (i.e. 2 to 64 mm). Figure 5.6 shows an example of modelled shear stress values at one of the sites at selected discharges; these values are then used to generate sediment entrainment maps (Figure 5.7).

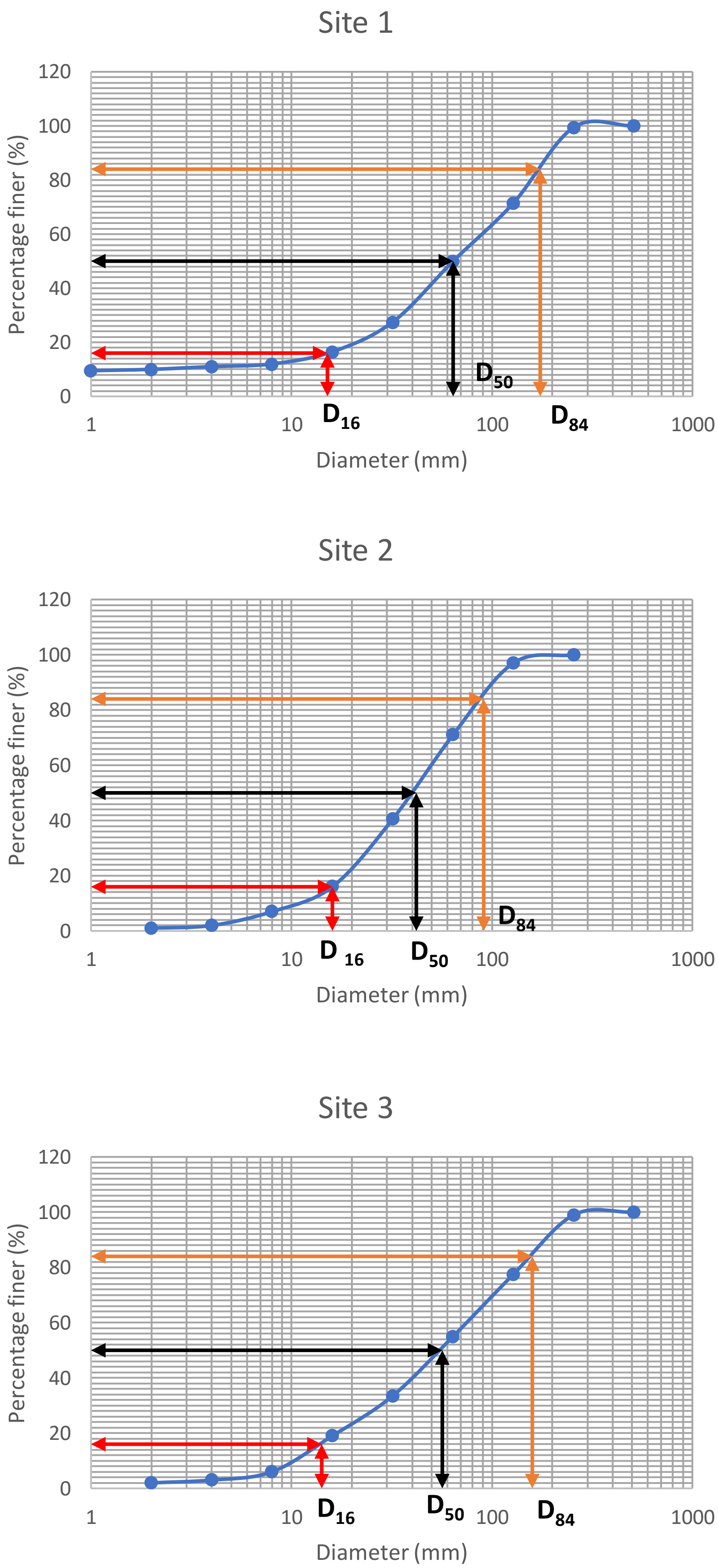


Figure 5.5 The grain size distributions for each site.

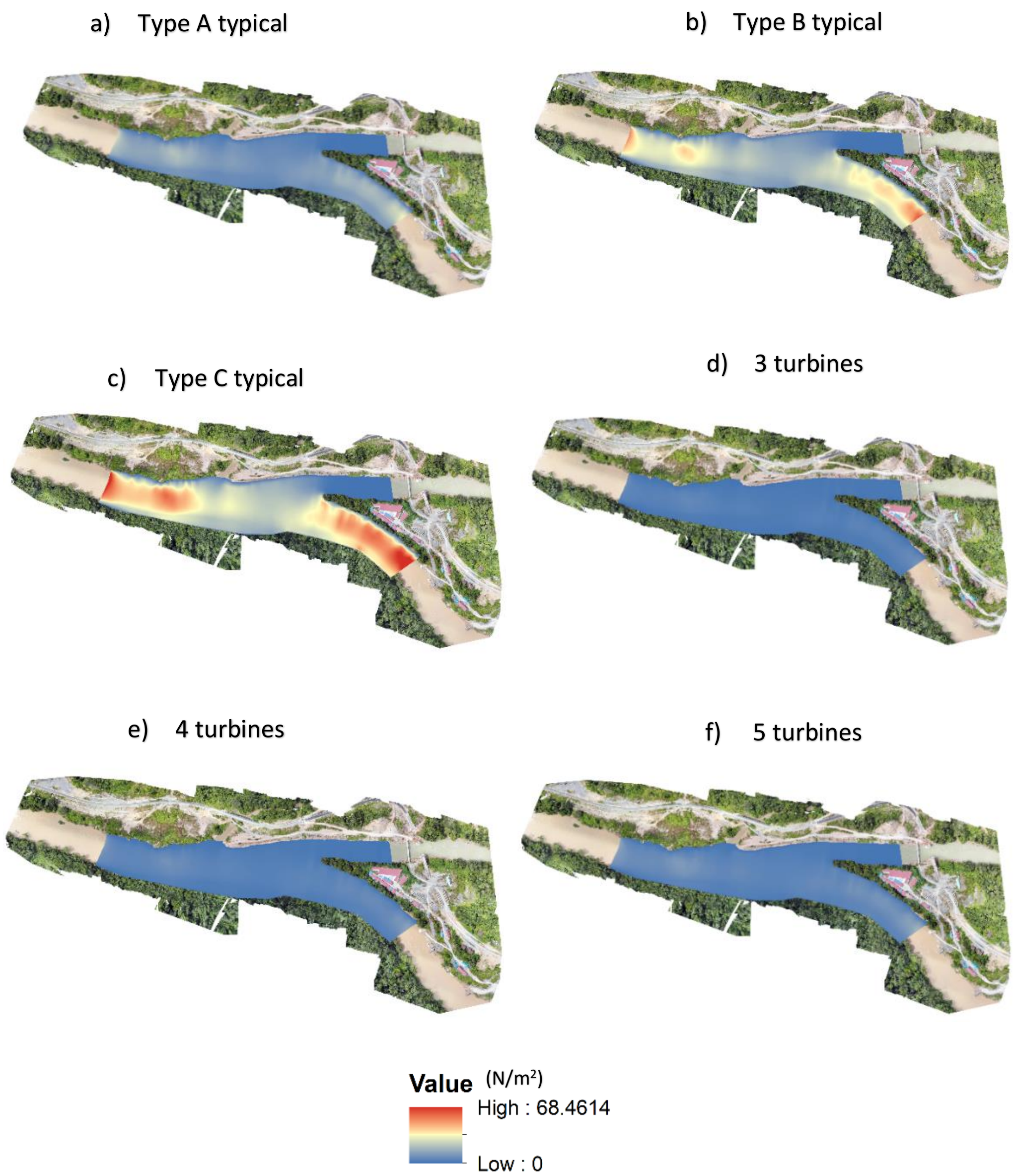


Figure 5.6 Spatial patterns of shear stress for each of the flows at Site 1.

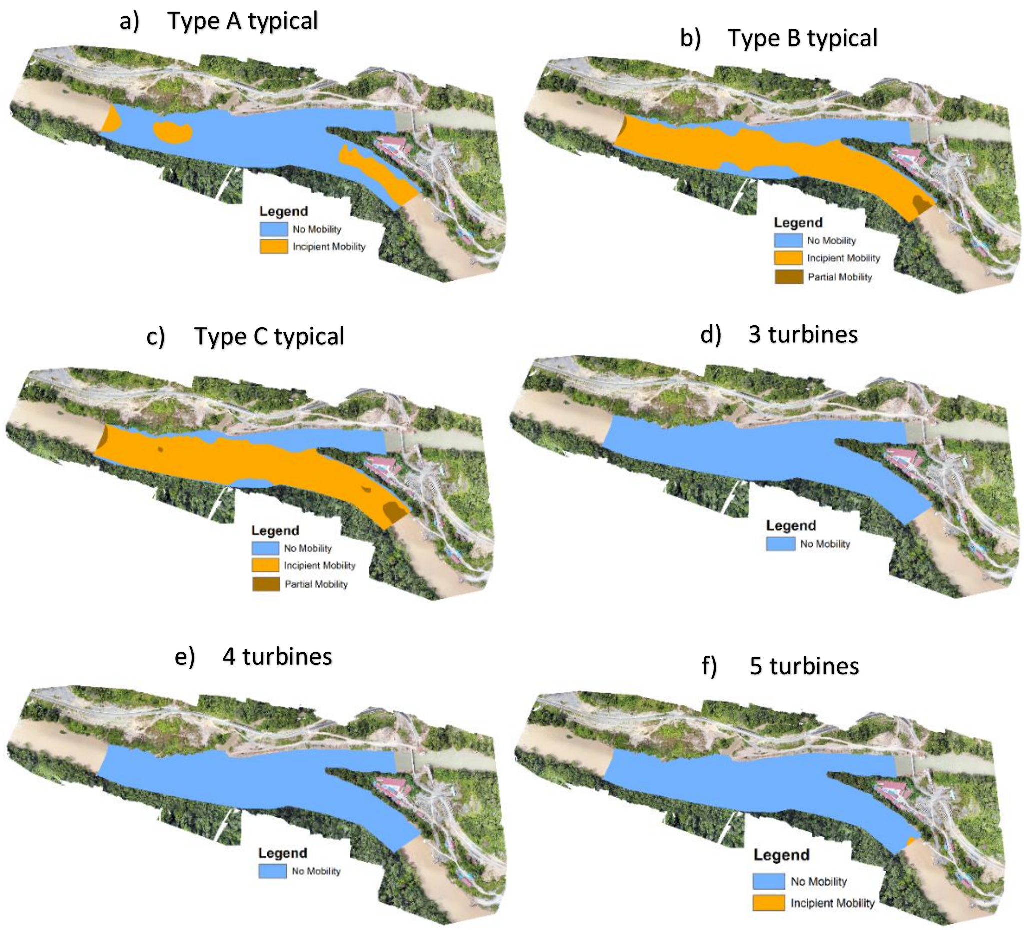


Figure 5.7 Parts of Site 1 where critical shear stress is exceeded for each of the flows.

Table 5.4 The critical shear stress values of each representative grain size for each site.

Sites	**Shear stress (N/m^2)**		
	D_{16}	**D_{50}**	**D_{84}**
1	14.73	44.7	103.54
2	14..46	30.46	57.58
3	13.61	39.54	94.31

The HEP flows are lower in magnitude than most of the natural high flow events at respective sites (see Table 5.3). The HEP flows of 3-5 turbine range from 372-620 m^3/s for Site 1, 487-812 m^3/s for Site 2 and 615-1025 m^3/s and equate to flow percentiles in the Q70 to Q40 range. By way of comparison, at Site 1 for example, event Type A which is the smallest of the natural event types, range from 463 - 1567 m^3/s; recreating flows at the higher end of this type (and Types B and C which are larger) would require at least 10 turbines.

The results indicate that on their own, none of the HEP flows (discharge resulting from 3, 4 or 5 turbines) will result in appreciable bedload transport at Site 1, the site nearest to the dam. Figure 5.8 shows the percent (%) area of each where shear stress exceeds critical values for the entrainment of the three representative surface grain sizes (D_{16}, D_{50} and D_{84}). At Site 1, flow at 3-4 turbines does not entrain any material of any of the 3 size classes. Only flow at 5 turbines entrains a small amount (0.3% of site area) of D_{16}. On the other hand, the lowest of natural flows (Type A) were able to entrain D_{16} (though not the large sizes), while Types B and C were able to entrain both D_{16} and D_{50} particles.

At Site 2, by allowing from increases in discharge that occur in the downstream direction, all flows were able to entrain all representative grain sizes with a percentage area of at least 45%. This shows that the particles are very mobile compared to the first site. This is clear in D_{16} as the percentage area of entrainment is at least 80% even during HEP flows.

At Site 3, larger natural flows such as Types B and C were able to entrain approximately 10% of D_{84}. This signifies that the particles at this site are slightly more mobile compared to Site 1, but less active than Site 2. HEP flows were able entrain some of the grain sizes at Site 3, depending on the number of turbines. None of HEP flows were able to entrain D_{84} sized material, while the % entrainment areas for the smaller grains were always lower than, or at the extreme low end, of the ranges of the natural events.

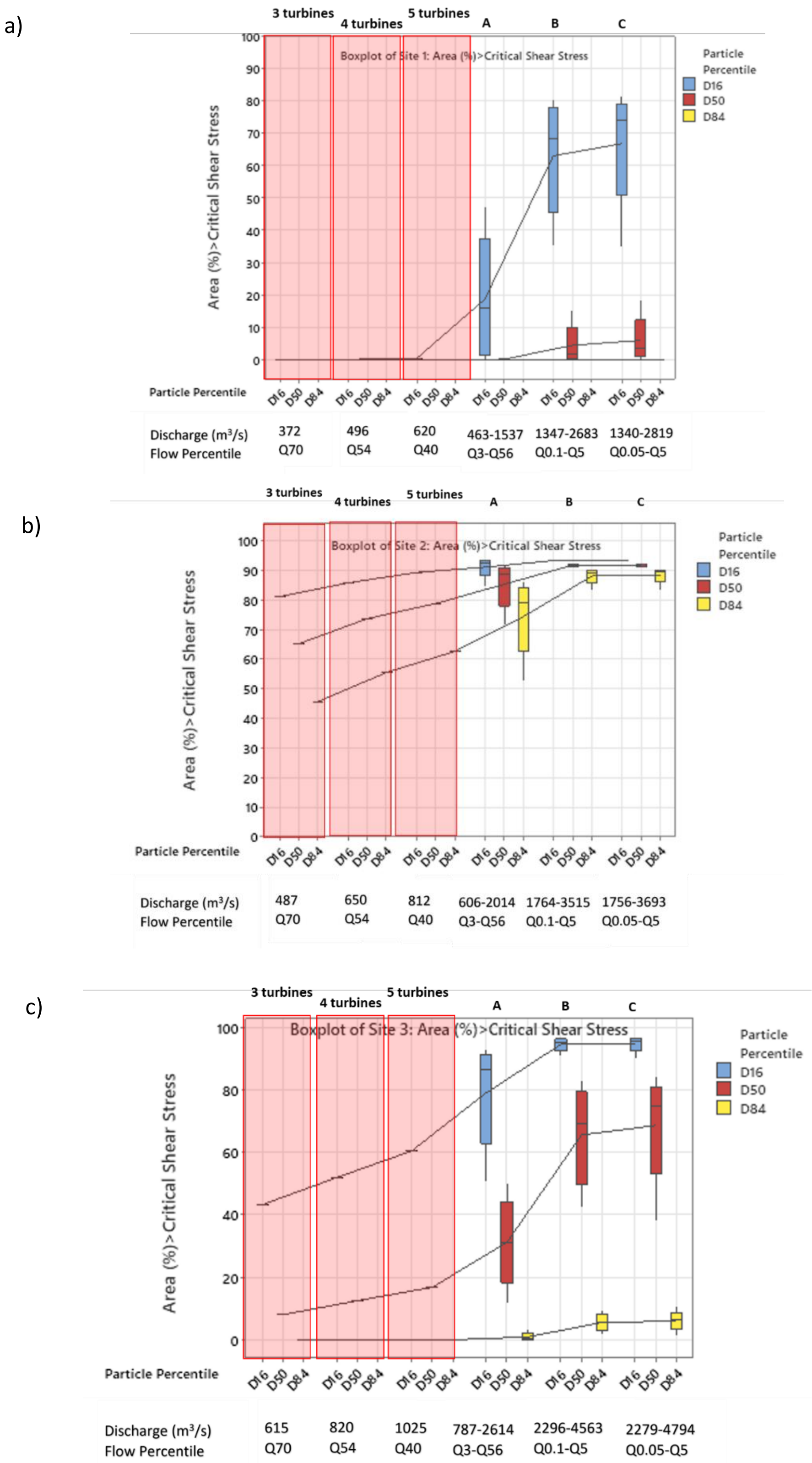


Figure 5.8 Entrainment of different sediment sizes during natural flood events (A-C) and HEP releases. (a) Site 1; (b) Site 2; (c) Site 3. Shear stress was predicted at the three HEP flows and the peak magnitude of 5 events from each of the 3 event types, covering the full range in

magnitude of events of each type. The height of the vertical bars indicates the variation in entrainment from the 5 events belonging to each type. The discharges and corresponding flow percentiles from these are shown along the base of the diagram.

Figure 5.9 shows the PCA for all sites using a set of metrics related to the average shear stress and the percentage area of entrainment for each representative grain size computed from the HEC-RAS® model. The PCA was used to allow comparison of the hydromorphic effects of discharges of different magnitude and understand the ways in which effects might differ most. The PCA used the shear stress values along with the % areas where critical shear stress for respective GSDs were exceeded. Overall similarity of effects was assessed using Agglomerative Hierarchical Clustering (AHC), which was used to identify statistically distinct clusters which were then plotted on the PCA biplots. Thus, the clusters indicate similarity of the effects of events/flow magnitudes within each cluster, which are distinct from those of other clusters.

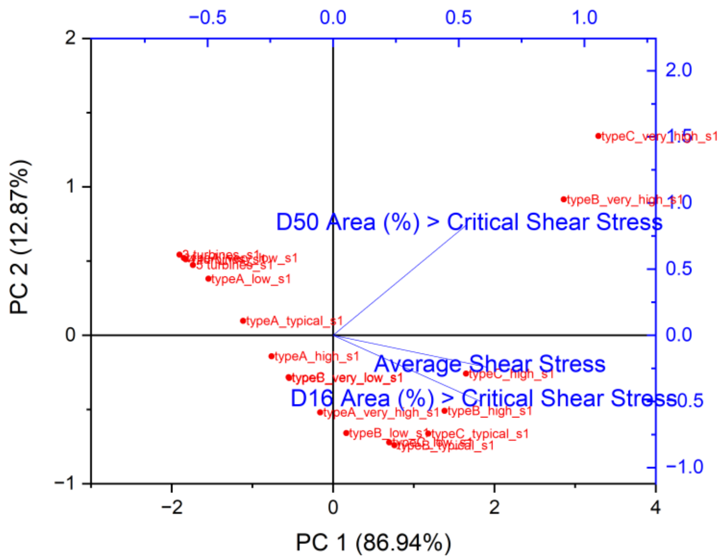
For Site 1 (Figure 5.9a and 5.9b), the vector lengths on the PCA are all very similar, indicating that none of the variables has a greater effect on overall differences between the hydrogeomorphic effects of the flow events than others. The PCA results in 3 clusters, with Cluster 1 being lower magnitude flows, consisting of all HEP flows and several Type A flows; Clusters 2 and 3 consist of higher magnitude flows, and is mostly made up of the Types B and C flows.

The Site 2 PCA (Figure 5.9c and 5.9d), the vector lengths are all very similar, indicating that none of the variables has a greater effect on overall differences between the hydrogeomorphic effects of the respective flow events than others. There are 3 clusters for this site, with Cluster 1 consisting of the lower magnitude flows, Cluster 2 consisting of natural events with slightly higher flow magnitude and Cluster 3 consisting flows of higher magnitude events (mostly made up of the Types B and C flows).

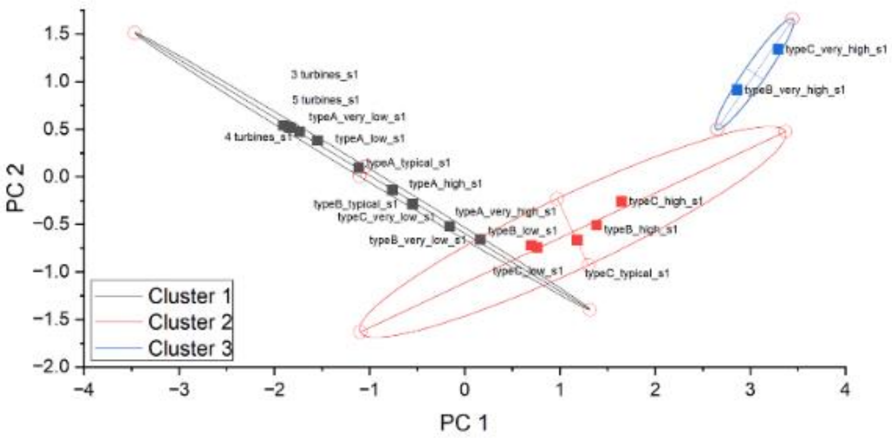
Like Site 2, Site 3 PCA (Figure 5.9e and 5.9f) suggests that there are 3 clusters of flow group. Cluster 1 shows the lower magnitude flows with all HEP. Cluster 2 is the cluster with flows of higher magnitude, mostly made up of the Types A and B flows and Cluster 3 consisting flows of higher magnitude events, mostly made up of flow Types B and C.

The PCA analysis shows that in terms of their effects, HEP releases of 5 turbines are similar to very small high flow events (i.e. smaller events within the Type A class, which is the smallest of the three classes). None of the variables has greater effect on overall differences between the hydrogeomorphic effects of the respective flow events than others, indicating that in essence, effects are mirrored for all the GSDs – those events that result in more entrainment of D_{16} also entrain more D_{50} and D_{84} sized material.

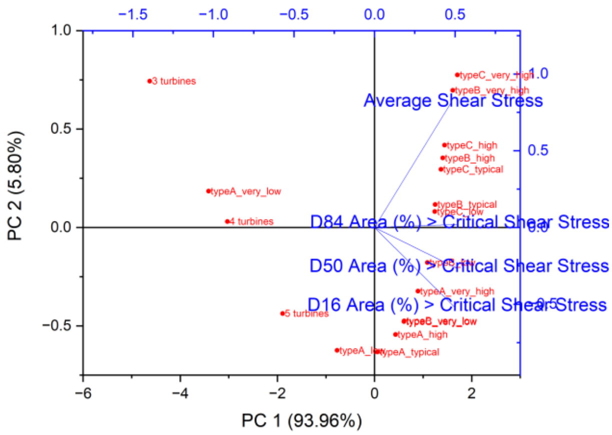
a)



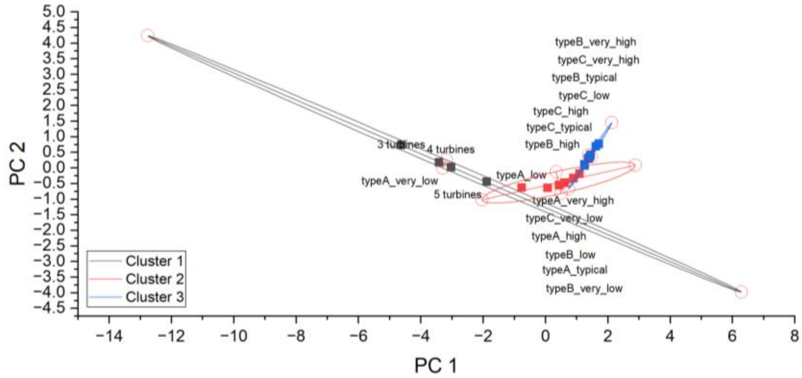
b)



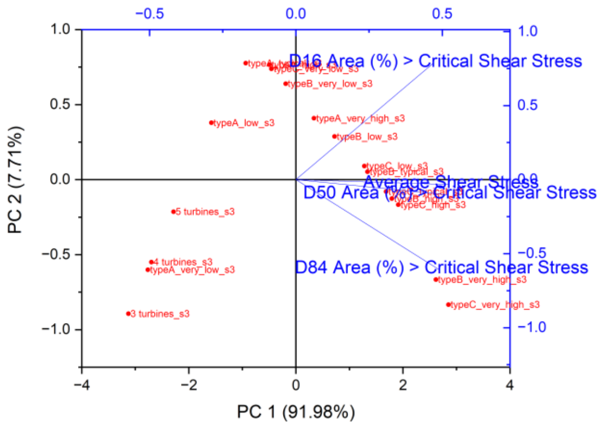
c)


PC 2 (5.80%)
PC 1 (93.96%)
Average Shear Stress
D84 Area (%) > Critical Shear Stress
D50 Area (%) > Critical Shear Stress
D16 Area (%) > Critical Shear Stress

d)


PC 2
PC 1
Cluster 1
Cluster 2
Cluster 3

e)


PC 2 (7.71%)
PC 1 (91.98%)
D16 Area (%) > Critical Shear Stress
Average Shear Stress
D50 Area (%) > Critical Shear Stress
D84 Area (%) > Critical Shear Stress

f)

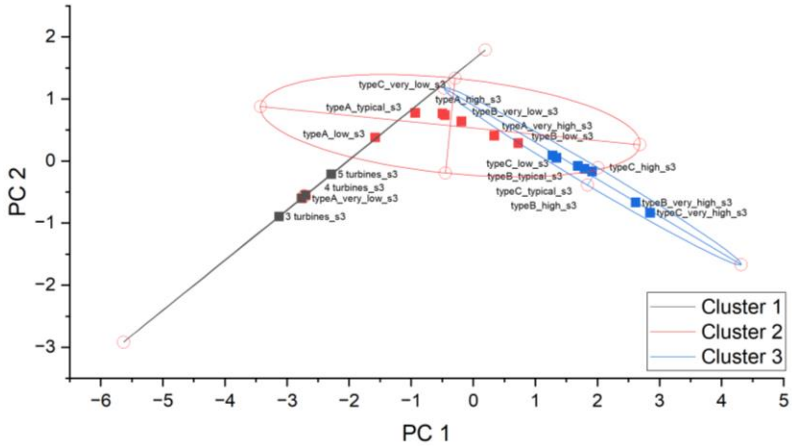

PC 2
PC 1
Cluster 1
Cluster 2
Cluster 3

Figure 5.9 PCA for all sites use a set of metrics related to the average shear stress and the percentage area of entrainment for each representative grain size computed from the hydraulic model.

These estimates represent worst case scenario where discharge at downstream sites scales directly with the magnitude of the HEP release. Table 5.5 shows the modelled entrainment at Sites 1, 2 and 3 when all the downstream tributaries are wet and contributing discharge at respective Q10 values. The discharges are appreciably greater than those simulated above, and correspondingly the areas of the sites where shear stress exceeds critical values for the entrainment of the three grain sizes are greater. At Site 3, discharge is estimated at approximately 1700 m^3/s (compared to 1025 m^3/s) and at this discharge, 84% of the site area has a shear stress that exceeds the entrainment threshold of D_{16}, 29% for D_{50} and 0.2% for D_{84}. Site 1 changes less because of its position very close to the dam. The Putai tributary joins in the middle of the site and so the flow increment resulting from this confluence affects only the downstream portion of the site. In the first simulations, no sediment was predicted to be entrained during HEP but in these higher flow ones, 1% of the site area has shear stress that exceeds the critical value for D_{16}.

Table 5.5 Entrainment of different sediment sizes during HEP release of 5 turbines together with higher flows (Q10) contributed by downstream tributaries to the mainstem at each study site.

Site(s)	Flow (m^3/s)	Particle Percentile	Area (%) > Critical shear stress
1	742	D_{16}	1
		D_{50}	0
		D_{84}	0
2	1031	D_{16}	90
		D_{50}	80
		D_{84}	64
3	1727	D_{16}	84
		D_{50}	29
		D_{84}	0.2

5.3.2. Effects of Impoundment on the Frequency of Competent Events

The analysis presented above suggests that under a regulated regime driven only by HEP releases, the lack of events with the competence to entrain sediment to the same extent as natural high flow events at the larger end of Type A, or of Types B and C will result in a riverbed that over time becomes immobile and armoured, especially in Site 1 that is closest to the dam. However, given the wet climate of the Baleh, the potential for dam overspill means that flows may exceed the magnitude of the HEP releases from time to time. SWAT® was used to assess such situations. Figures 5.10 and 5.11 show ArcSWAT® simulations showing the effect of dam operation (HEP production at 5 turbines) on discharge at Sites 1 (nearest to dam) and 3 (furthest from dam) in dry, typical, and wet years. As the focus here is on sediment entrainment, a continuous HEP release of 5 turbines was used for the simulation. The plots show the downstream flow regime with the dam operating at 5 turbines; for comparison they also show what the flow regime would have been like in respective years without the dam.

The simulations show that with the dam constantly generating maximum HEP, flows in the downstream river increased above the 5 turbine discharge value around 10-15 times each year, even during dry years. These periods were during wet conditions when the reservoir was overspilling as a result of rainfall and hence high flow inputs from sub-catchments that feed into the reservoir. Therefore, as shown by the difference between the blue (regulated) and orange (unregulated) lines for same climate regime, the peaks of these 10-15 events are relatively smaller when a dam is in place, but at least flows do exceed the 620 m^3/s (5 turbine HEP flow) on a number of dates.

The maximum discharge predicted by SWAT® for Site 1 with the dam in place and operating with 5 turbines was 1201 m^3/s. This maximum regulated flow compares to the natural regime where flow frequently exceeds 1500 m^3/s and exceeded 2000 m^3/s on six occasions over the year. Magnitudes of around 1000 m^3/s take flows into mid range of event Type A at Site 1 so entrainment of D_{16} and D_{50} can be expected in these conditions.

At Site 3 (around 40 km downstream of the dam), while the effect of dam is still noticeable, flow inputs from downstream tributaries mean that flow peaks regularly exceed 1000 m^3/s and can reach 2000 m^3/s (Figure 5.11). Sediment entrainment similar to that associated with natural Type A events (entraining D_{16} and D_{50}) can be expected under such conditions at this site (as per Figure 5.8).

While flow accumulated fairly continuously downstream, as a result of inputs of water from tributaries, the flow contribution to Q10 by the main tributaries at each of the sites are calculated using the SWAT modelling results prepared by Lum (unpublished MRes thesis) (Table 5.5).

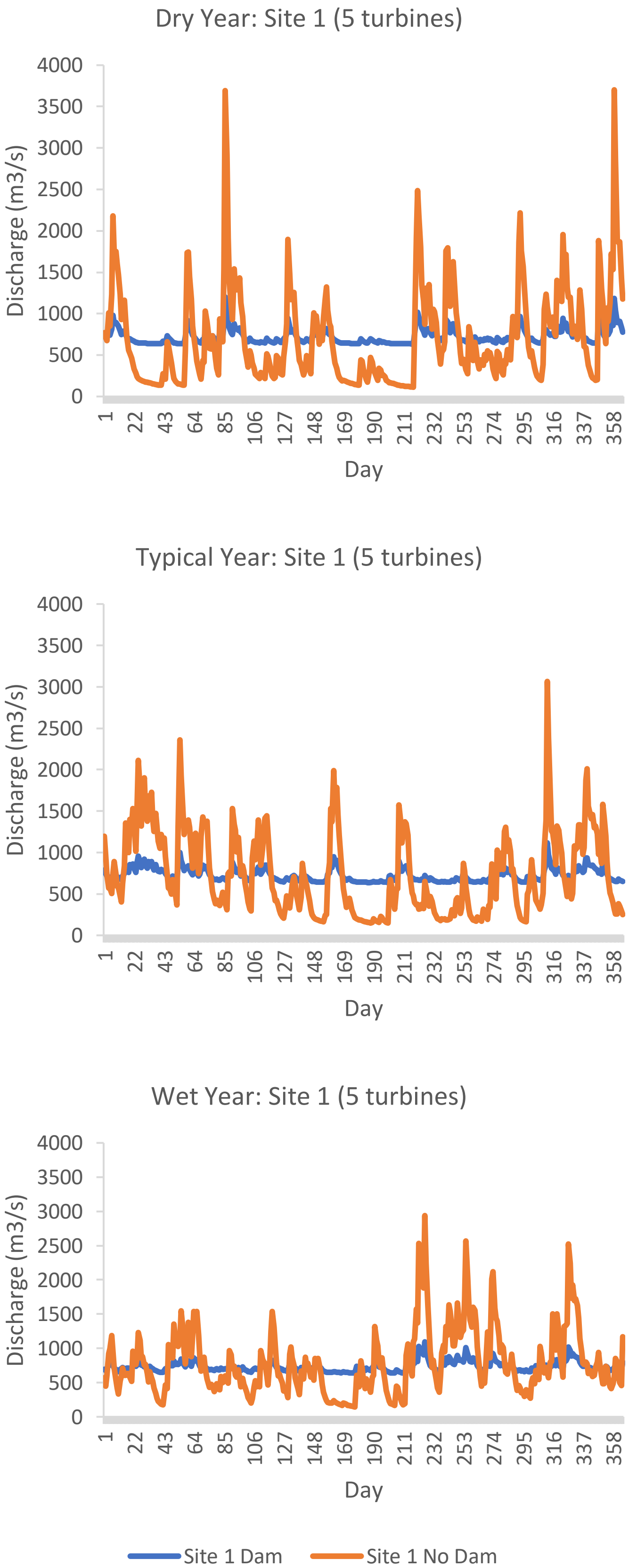


Figure 5.10 ArcSWAT® simulation showing the effect of dam operation (HEP production to 5 turbines) on discharge at Site 1 (nearest to dam) in dry, typical and wet years.

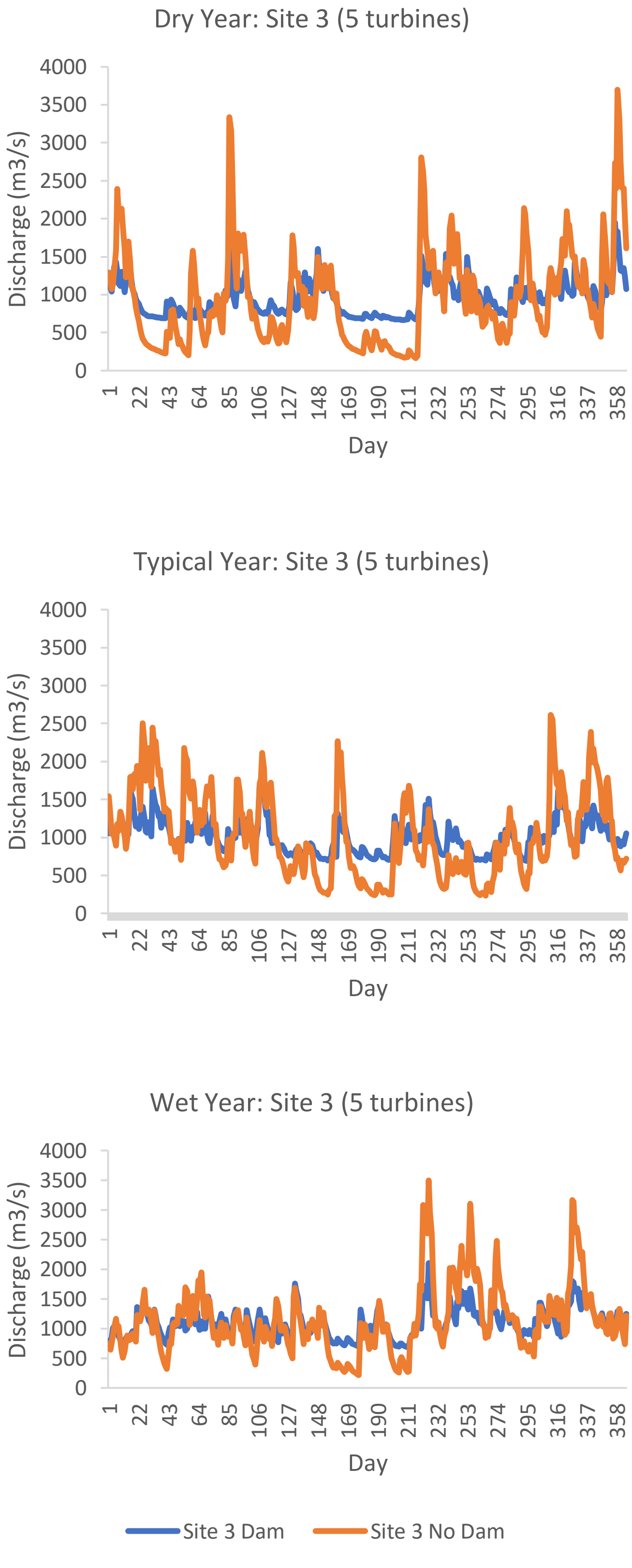


Figure 5.11 ArcSWAT® simulation showing the effect of dam operation (HEP production to 5 turbines) on discharge at Site 3 (furthest from dam) in dry, typical, and wet years.

5.3.3. Low Flows in the Baleh and Implications for Habitat

5.3.3.1. Low Flow Magnitudes

The insights into the hydrological regime of the Baleh provided by HyFFlow (Chong et al., 2021b) can be found in Chapter 3. Flow duration curves for the three study sites are shown in Figure 5.12, from which we can extract information about the overall flow regime. The Indices of Hydrological Alteration (IHA) software was used to extract additional information about the frequency and duration of low flow events of different magnitudes (e.g. typical duration of individual events that are lower than Q95) and baseflow values.

Natural extreme low flow (Q95) at the dam site is 172 m^3/s. Release of water from only a single turbine (124 m^3/s) equates to the Q99 at the site. Thus, one turbine results in a flow that occurs on average for around 3-4 days each year. However, the wet and dry seasons have different flow percentiles, as shown for Site 1 in Figure 5.13. The wet season Q95 is 243 m^3/s and the dry season Q95 is 143 m^3/s. In the long-term natural data (1967-2017), the mean duration of events of Q95 magnitude is 3 days, and the Coefficient of Variation (CV) is 1.25 days. The mean number of such events per year is 2, with CV of 2.3.

Baseflows during the wetter months are rather variable, but typically range between 320-420 m^3/s (Figure 5.14). During the dry months of June to September inclusive, the natural median baseflow is 250-300 m^3/s. May and October are ‘transitional’ months - on average, baseflow magnitude sits between the more distinctly dry and the distinctly wet months, and tends to be characterised by variability, with progressive reductions in baseflows through May and progressive increases during October.

Figure 5.15 shows the number (frequency) of flow events below median baseflow magnitude in each month, based on the long-term time series data. The figure illustrates sesasonal differences in the frequency of these low flow events – for example, over the November to April period, the number of events is typically 2 per month, while in the dry season of June to September, this rises to typically 3 per month. As indicated in Table 5.6, these events are short in duration, typically 3 days.

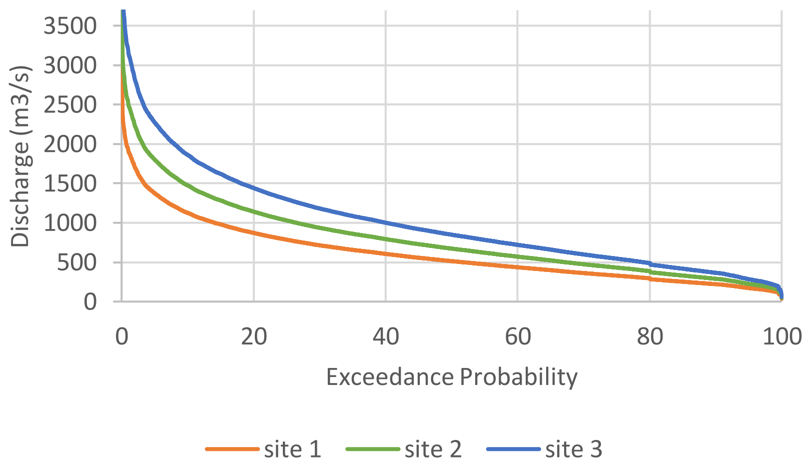


Figure 5.12 Flow duration curves for study sites on the Baleh River. Site 1 is the dam site. Values show the percent of time that particular discharges are exceeded. The median flow is therefore the discharge that is exceeded for 50% of the time (Q50); at the dam site, Q50 is approximately 500 m^3/s.

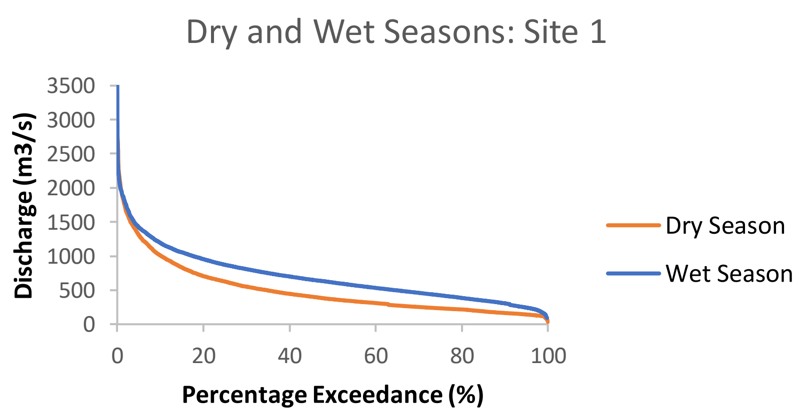


Figure 5.13 Flow duration curves for Site 1 illustrating differences between wet months (November to April) and dry ones (June to September inclusive).

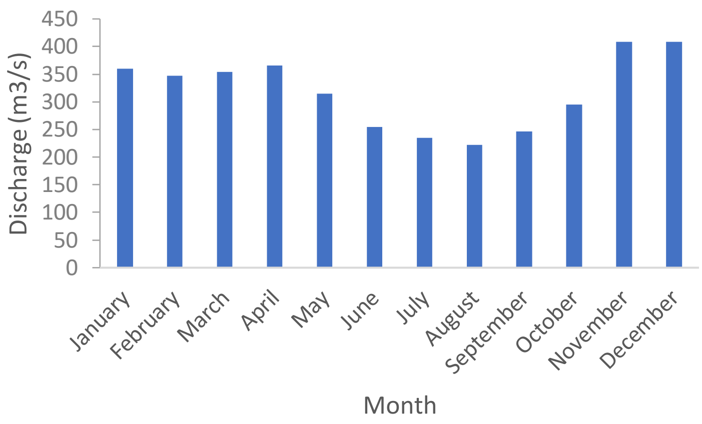


Figure 5.14 Median monthly baseflows in the Baleh (1967-2017).

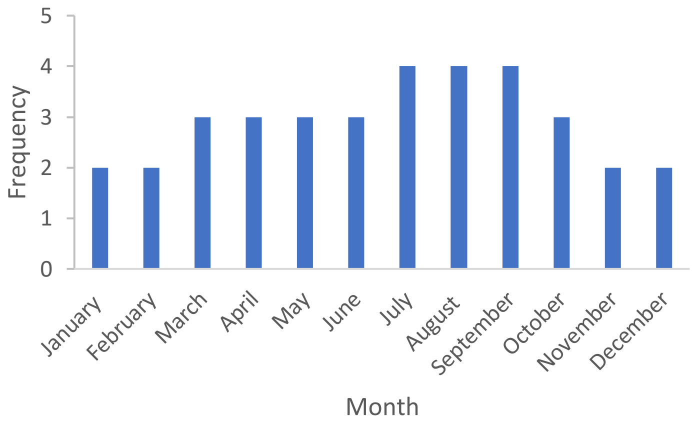


Figure 5.15 Frequency of flows between median baseflows and Q95 over an annual cycle in the Baleh River.

Table 5.6 Summary of magnitudes, timing, frequency, and duration of low flows, and flows between low flows and median baseflows.

Magnitude (m^3/s)	Flow percentile	Timing	Frequency	Duration
143	Q95 in dry season	June to September	<5 times per year	3 days
243	Q95 in wet season	Novermber to April	<5 times per year	3 days
<250	Q86	June to September	3 times per month	3 days
<350	Q75	November to April	2 times per month	3 days

5.3.3.2. Hydraulic Heterogeneity

Figure 5.16 shows the GAM plots of the coefficient of variation (CV) of velocity against discharge for each site. The velocity values are extracted from the HEC-RAS® models as detailed in Section 5.2.5.1.

At all three sites, CV (i.e. hydraulic heterogeneity) is relatively high at lower flows. The CV values that are associated with Q95 and Q99 are approximately 0.28 and 0.29 respectively at Site 1; 0.53 and 0.61 at Site 2; 0.63 and 0.64 at Site 3. Heterogeneity progressively reduces at Site 1 as discharge increases, while at Sites 2 and 3 the lowest CVs are associated with discharges that fall within the range of moderate to high natural flow events (i.e. in the range of event Types B and C); at these two sites extremely high flows (> approx. 2500 m^3/s at Site 2 and 3500 m^3/s at Site 3) result in greater heterogeneity than moderate to high flows.

Figure 5.17 shows heterogeneity over an annual cycle (day 1 to day 365) modelled according to discharge on respective days. Data for twelve different years, spanning dry, typical and wet years (4 years of data for each hydrological year) are modelled across all sites. As evident from Figure 5.16, heterogeneity rises and falls in response to changes in discharge and accordingly, Figure 5.17 shows that there are two periods of low hydraulic heterogeneity – one in the last few months of the year associated with higher flows, and another in the first few months of the year which are also typically high flow months. Note that during the height of the dry season (July and August) heterogeneity is relatively high. Thus, during the dry season even though in many locations’ velocities may be low, some high velocity locations remain and so habitat retains some heterogeneity.

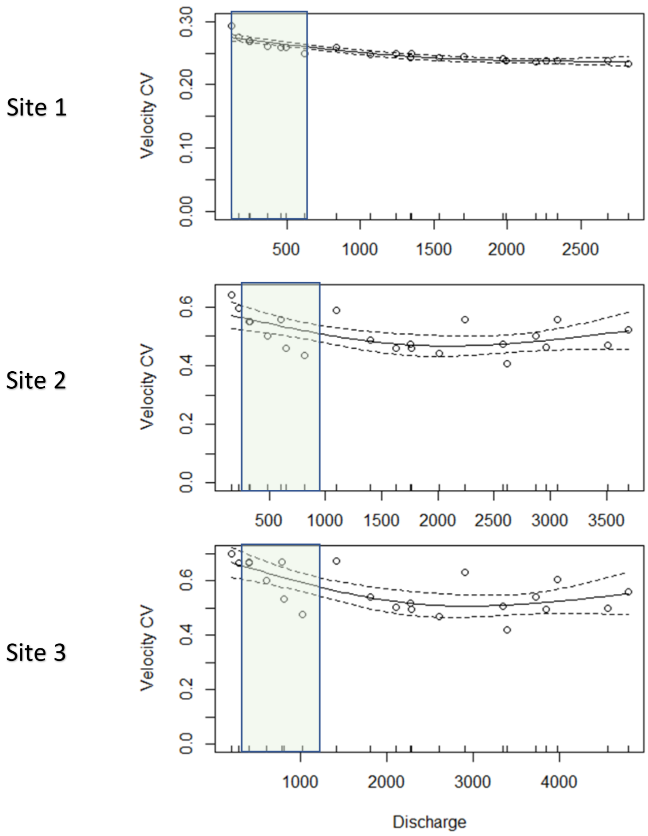


Figure 5.16 Relations between discharge and hydraulic heterogeneity for the study sites. The coefficient of variation in velocity is used as the index of habitat heterogeneity. Lines show GAM models with 95% confidence intervals (solid and dashed lines respectively). The boxes show the ranges of some possible dam operational discharges that are discussed later in the chapter.

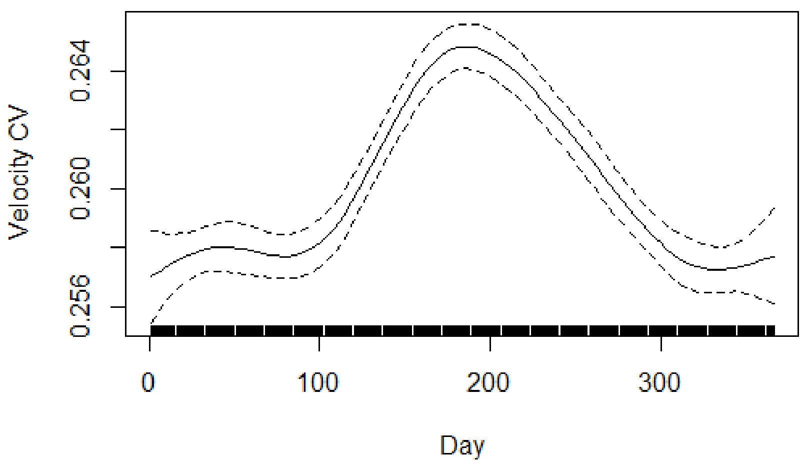


Figure 5.17 Modelled values of hydraulic habitat heterogeneity (CV of velocity) as a function of discharge over an annual cycle. Modelled line is a GAM with 95% confidence intervals (full and dashed lines respectively) fitted to 12 different years of data.

5.3.3.3. Exposure of Gravel Bars

The exposure of gravel bars as flows drop represents another way that flow alters habitat heterogeneity – the exposure of bars creates a mosaic of wet and dry areas, in parallel with development of standing (back) water areas as certain parts of channel become isolated from the main flow. An example of this can be seen at Site 3 in Figure 5.18.

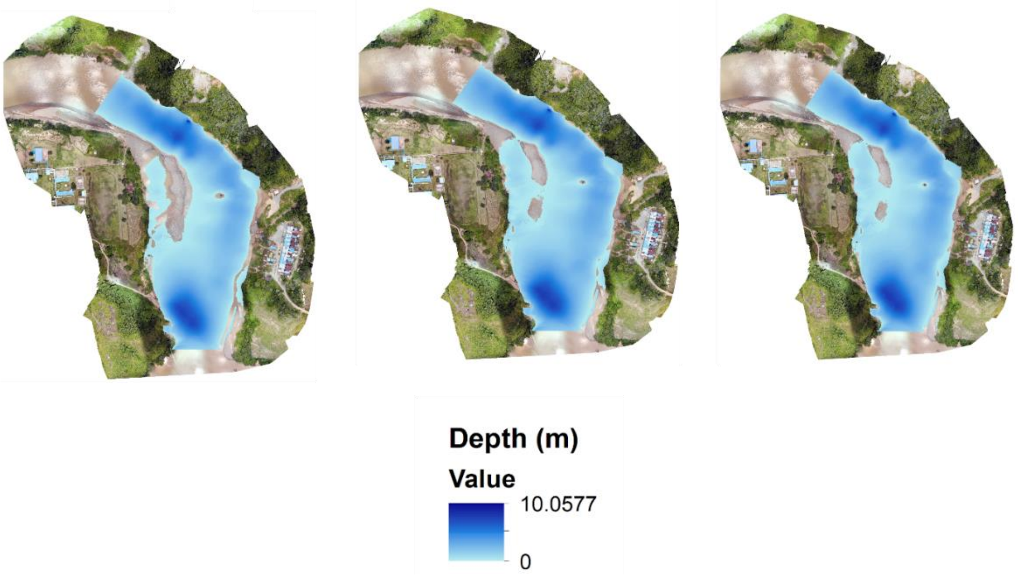


Figure 5.18 These diagrams show parts of the site where gravel bar is exposed at discharges that represent typical baseflow values in wet (right) and dry (left) seasons, and months that can be considered transitional between these extremes (middle), as per the seasonal baseflow plots (Figure 5.14).

5.4. Discussion and Conclusions

5.4.1. Summary of Main Findings

The work described in this chapter provided insights into the potential effects of the regulated flow regime on sediment entrainment in the Baleh, as well as how low flows influence hydraulic conditions and the extent to which natural gravel bars are exposed. The analyses were designed to provide information that would be useful for designing functional flows. The following text summarises the main findings with respect to each of the objectives, and then provides some recommendations for how this information can be translated into flow management.

Objective 1: To understand the effects of a range of natural and anticipated dam operational flows on sediment entrainment

In general, the results indicate that as flow magnitude increases, the greater the spatial extent of sediment entrainment and, in turn, movement of larger material. On their own, none of the HEP flows (discharge from 3–5 turbines) will result in appreciable entrainment of material in any of the 3 size classes at the site nearest to the dam. Even at 5 turbines, only 0.3% of the site area had shear stress exceeding the entrainment threshold of the smallest grain size (D_{16}) while the smallest of the natural high flow events (Type A) was able to entrain this size across an estimated area of 40% of the site; natural flow Types B and C were able to entrain both D_{16} and D_{50} particles. Due to the increase of discharge at the more downstream sites, HEP flows were able entrain all the representative grain sizes at Site 2 (at least 45% of site areas from each grain size) and at least 10% of the area of D_{16} and D_{50} at Site 3, depending on the number of turbines. While none of the HEP flows could entrain D_{84} at the most downstream site, larger natural flow events belonging to Types B and C resulted in shear stress over approximately 10% of the site area exceeding the critical values for this coarse sediment.

The second set of simulations based on higher inflows from the tributaries indicated that, when the catchment is wet, more entrainments can be expected, especially at Sites 2 and 3; e.g. 80% and 29% of respective sites areas would experience shear stress exceeding the critical values for D_{50} sediment sizes. These flows are equivalent in magnitude to larger natural events of Type A and smaller sized Type B events, and the extent of entrainment therefore corresponds to these small to moderate floods. While the first set of simulation suggested that under a regulated regime, the bed would be static and armouring would follow, the scenarios focussed on wetter conditions indicated that flows and patterns of entrainment could reach those akin to small to moderate natural events.

Objective 2: To understand how flow magnitude and water stage affect hydraulic habitat heterogeneity

The greatest heterogeneity in velocity (i.e. highest CV) occurs at lower discharges. As discharge increases, the hydraulic habitat heterogeneity decreases until a point at which heterogeneity tends to remain the same or increases only slightly. The high heterogeneity at low discharges is because the riverbed begins to affect velocities more as the water becomes shallower, so differences can be seen between habitats that are drowned out at higher flows/stages. Low hydraulic heterogeneity occurs in the first and last few months of the year (wet season), with heterogeneity relatively high during the middle months of the year (dry season). The analyses also indicated that at lower flows gravel bars become exposed, and these further contribute to habitat heterogeneity, creating a patchy mosaic of wet and dry areas. Exposed riverine sediment habitats exhibit a great deal of heterogeneity in terms of their physical characteristics and this positively affects invertebrate diversity as well as creating habitat of rare species (Sadler et al., 2004).

Objective 3: To assess the timing and frequency of important low and high flows

The analysis on high flows suggests that in order for substantial bedload transport to occur, dam overspill is needed to increase flows to the magnitudes of around 1000 m^3/s during the wet season over the year. Dam overspill occurs during wet periods when high flow inputs from sub-catchments that feed into the reservoir that cause flows to exceed the magnitude of the HEP releases. The frequency of these flows occuring is 10 to 15 times a year.

As for high flows that are potentially significant for sediment entrainment, we learn that from HyFFlow, as detailed in Chapter 3 (Chong et al., 2021b), Type A events which could be simulated and created by artificial releases designed to mimic their shape as this event type has rather clear seasonal patterns of occurrence, so releases could potentially be made to mimic their timing. Type A events peak at around 7–9 days at between 100–900 m^3/s (above respective time baseflow levels), and lasts for around 20 days. This event has peaks of occurrence in late May to early June, and then November and December, with frequencies of around 15 times per year.

As for low flows, these occur in the dry season of June to September inclusive; with flows between median baseflow and Q95 normally last around 3 days, with frequencies of 3 times per month (Figure 5.15).

5.4.2. Flow Recommendations

For the purpose of providing recommendations for a functional flow regime to maintain processes that create riverbed habitat (sediment entrainment, which leads to transport of bedload) and habitat heterogeneity, assessment of the magnitude, timing, duration and frequency of important low and high flows is necessary. The following recommendations are based on integration of the results summarised above which concern the effects of events of different magnitudes, their timing, duration and frequency.

5.4.2.1. Low Flows

Magnitude

The seasonal baseflow regime provides the starting point for time-specific **normal minimum flow recommendations** (‘target minimum flows’). It is suggested that the minimum permissible flow release under normal circumstances should reflect median monthly baseflow values (as per Figure 5.14). These values range from 222 m^3/s to 408

m^3/s but vary across the year as a reflection of rainfall patterns. These natural baseflows – which are hence the target minimum dam releases – are shown by the green line in Figure 5.19.

Note that May and October are intermediate months, reflecting the transition from wet to dry and from dry to wet seasons respectively. Accordingly, some flexibility in flow releases from the dam should be permitted in these two months; i.e. rather than rigidly following the statistical median monthly baseflow values (305 m^3/s), depending on water availability and antecedent conditions, releases between 295 m^3/s - 314 m^3/s would be permissible.

Under the natural flow regime instantaneous discharges drop below the median monthly baseflow values from time to time. This happens during excessively dry periods. Thus, during such dry periods, flows can be allowed to drop below the normal target minimum flows. These lower values can be seen as **absolute minima.** It is suggested that season specific Q95 values can be used for these absolute minima - 143 m^3/s for the dry months, and 243 m^3/s for the wet months, represented by the orange line in Figure 5.19.

Frequency and duration

Dam releases of the absolute minima should not extend for a continuous period of more than 5 days, to match the natural duration of such events. Also, such low flows occur no more than 5 times per year, so dam operation should target no more than 5 such low flow episodes each year. Flows can be permitted to drop to these levels in periods of little rainfall when inflows to the dam are also low.

The target minima i.e. based on median monthly baseflows should last around 3 days with a frequency of at least 3 times per month during the wet season, and 2 times per month during the dry season. These two flow levels (i.e. target instantaneous minimum flow and target baseflow) are compared with the long-term median flow values that range from 311 m^3/s to 676 m^3/s, represented by the purple line in Figure 5.19.

It is important to stress that (a) these are minimum flows so dam releases will regularly be greater than these values, and (b) they are based only on flow magnitude, duration, and frequency statistics. To 'check' the implications of these for habitat, we looked at hydraulic heterogeneity and exposure of gravel bars.

The green boxes on Figure 5.16 showed the discharge ranges recommended for target normal operational flows and the absolute minima. These indicated show that hydraulic habitat heterogeneity (while dropping) remains relatively high across this flow range. Thus, there are no concerns that the minimum flows will lead to reductions in hydraulic habitat heterogeneity across the sites. These analyses suggest that from time to time, the dam should not produce HEP, and flows should be allowed to drop to these targets. The number of turbines that is required to be operated to achieve both target normal operational flows and the absolute minima are illustrated in Figures 5.19b and 5.19c. For the absolute minima, 1 to 2 turbines should be operated, whereas the target for normal operational flows requires 2 to 3 turbines.

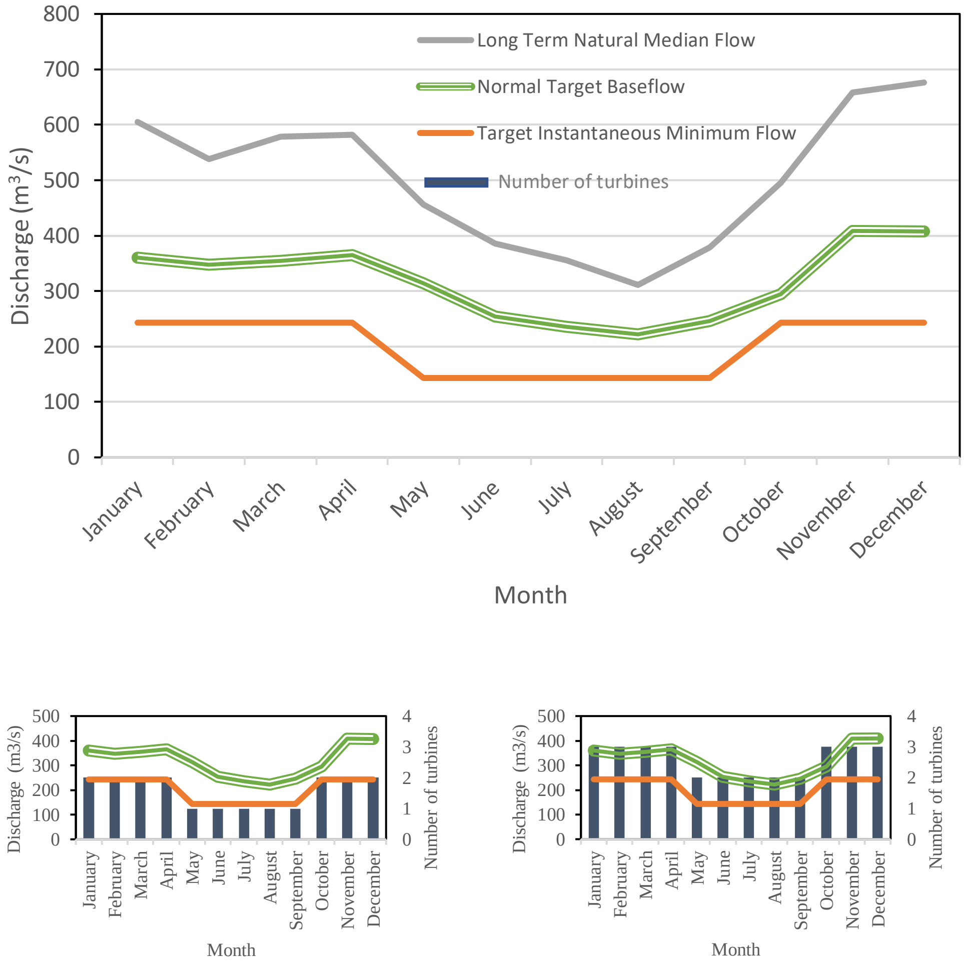


Figure 5.19 (a) Schematic representation of minimum flow recommendations. The orange line is the absolute minimum acceptable release from the dam; such flows should be permitted to last for no more than 3 consecutive days and 5 times each year. Flows should be permitted to drop to these levels only during periods of very dry weather. The thick green gives the values (for each month and season) that should be targeted for operation in non-exceptional weather conditions; these match natural baseflows. These two levels are compared with the long-term median flow value; (b) schematic representation of minimum flow recommendations with the number of turbines needed for the absolute minimum (i.e. orange line); (c) schematic representation of minimum flow recommendations with the number of turbines needed for the target for normal operation (i.e. green line).

5.4.2.2. High Flows

Analysis of the long-term natural hydrograph (Chapter 3) indicated that a number of statistically distinct types of high flow event occur in the Baleh. These events are defined by their peak discharge value, duration and rates of rise and fall. The smallest of these types (Type A) contains individual floods with peak discharges that range from 463-1507 m^3/s at Site 1 (dam site), and this event type overall has a median peak of 981 m^3/s. These values compare to normal dam operation at 4 turbines which results in a flow of 496 m^3/s, and a maximum possible operational release of 620 m^3/s (5 turbines).

The HEC-RAS® modelling work was designed to show the competence of the natural events and various HEP releases to entrain representative sediment grain sizes. Note that this modelling was relatively simple, in that predicted how much of the bed area might be entrained at respective event peak discharges (i.e. it did not model how the duration or shape of the events might influence entrainment). The analysis indicated that operation at 4 turbines does not generate flows competent to entrain appreciable amounts of the bed material at any of the study sites, while even releases at 5 turbines equate only to the very smallest events that belong to natural event Type A. However, when HEP coincides with periods when the river is at relatively high flow (i.e tributaries are flowing at rates approximating their Q10 values), entrainment similar to that associated with small to moderate natural events can be expected. This result reflects Winton et al. (2019) who suggested that the influence of tributaries entering between sites is significant in entraining and transporting sediments, and they play a role in the recovery of the river to a more “natural” state. Therefore, key to maintaining natural fluvial dynamics in the Baleh would be to ensure that flow is released through 5 turbines when the river is otherwise at high flows, to help support sediment entrainment. The operationalisation of this recommendation requires some further work, so that for example, real-time flow gauging in the downstream river allows decisions to be made about dam releases.

The SWAT® modelling results of dam overspill indicated that sediment entrainment can also be expected during such times. However, controlling the dam and lake levels to allow for 'managed' overspill is likely to be more complex than simply producing HEP when the river is already at high discharge. Hence, overspill which can potentially increase flow from 620 m^3/s to 1200 m^3/s at Site 1 (refer to Section 5.4.1 for more details) creates a second set of opportunities for sediment entrainment to occur.

5.4.3. Concluding Remarks

Integration of important high and low flows into dam operational regimes is vital to maintain habitat formation and heterogeneity. The findings of this study are significant in Southeast Asia as functional flow studies are uncommon in this and other tropical regions (see Chong et al, 2021a for a recent review). Although some broadly similar studies have been conducted, these differ in important ways from work presented here. Arias et al. (2014) quantified how hydropower development in the Sesan, Srepok, and Sekong rivers would alter the hydrology of the Tonle Sap's floodplain. Their study focussed on environmental flow criteria based on the specific biological needs of this system. However, as discussed earlier in this thesis, such biological criteria are not available for the Baleh and flows to support biological functions could not be modelled. Abam (1999) discussed the effects of multiple dams on the downstream Niger Delta. While they looked at sediment transport, their work focussed on coastal barriers areas. While both Stevaux et al. (2009) and Basson (2004) evaluated change in sediment transport associated with damming in tropical rivers, neither study applied the results of their work to propose specific flows to support fluvial functions. To the best of knowledge, no published studies have combined catchment (SWAT®) with channel (HEC-RAS®) models to evaluate the implications of both high and lows flows on tropical rivers and generate specific functional flow recommendations to guide management of tropical dams.

A further novel aspect of the present work is that it has been undertaken before dam closure. This allows us to implement functional recommendations in advance of construction, rather than retrofitting them to a river that has been regulated for some time (which most often happens). The flow recommendations however need to be reviewed in the light of ongoing monitoring to assess impacts on sediment dynamics and habitat conditions. This issue will be discussed in more detail in the following chapter.

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CHAPTER 6
Synthesis

6. SYNTHESIS

6.1. RESEARCH CONTEXT

Dams have been constructed worldwide over a time period extending back to the earliest human civilizations, but a major period of current expansion is focused on the tropics. While their deleterious impacts have long been acknowledged, our understanding of the full range of dam effects on tropical rivers remains limited. The concept of functional flows (FF) is widely discussed in the scientific and management literature, yet application in tropical regions remains largely unexplored. This thesis provided a unique opportunity to conduct research on the Baleh River prior to dam construction, allowing for the development of a functional flow regime proactively rather than reactively.

This thesis covered four main areas, all leading to the development of functional flow recommendations to guide dam operation. It included a comprehensive review of current knowledge on the impacts of dams in tropical rivers (Chapter Two), detailed hydrological characterisation of the Baleh to understand its hydrological regime and describe this regime in a statistical way (Chapter Three), analysis sediment connectivity across the catchment (Chapter Four), and finally, the analysis of the functional importance of high and low flows in the river (Chapter Five).

Formally, this thesis aimed to provide functional flow recommendations for Baleh dam based on an understanding of catchment and channel dynamics. Specific objectives were to: (i) develop a full statistical understanding of the natural hydrological regime of Baleh River, (ii) identify critical habitat forming discharges (those responsible for coarse sediment entrainment and transport) and relations between discharge magnitude and hydraulic habitat heterogeneity, (iii) to assess the impact of the dam and other land use changes on sediment connectivity, and (iv) provide specific recommendations for dam operation to support sediment entrainment and maintenance of habitat heterogeneity, and for management of lake levels to limit changes in connectivity. The following sections summarise findings with respect to these objectives, their wider implications, and then discuss what is needed for the Baleh going forward.

6.2 KEY FINDINGS

A major programme of dam building is underway in many of the world's tropical countries. Chapter Two in the thesis raised the question of whether existing research is sufficient to fully understand the impacts of these dams on tropical river systems. This chapter provided a systematic review of what is known about the impacts of dams on river flows, sediment dynamics and geomorphic processes in tropical rivers. It considered the issue of connectivity, both in terms of longitudinal connectivity and the connectivity between stream networks and their catchments. The review concluded by arguing that although research on tropical rivers remains scarce, existing work is sufficient to allow us to draw some very broad, general conclusions about the nature of hydromorphic change in response to impoundment: tropical dams have resulted in reductions in flow variability, lower flood peaks, reductions in sediment supply and loads, and complex geomorphic adjustments that include both channel incision and aggradation at different times and downstream distances. At this general level, impacts are consistent with those observed in other climate regions. However, the review also stressed that studies are too few and variable in their focus to either: (i) determine whether some of the more specific aspects of change observed in tropical rivers (e.g. time to reach a new, adjusted state, downstream recovery distance) differ consistently from those in other climate regions, or (ii) predict with any degree of precision what the likely impacts of a given tropical dam will be. The review helped stress the need for research that incorporates before-after comparisons of flow and geomorphic conditions, and for the wider application of tools available now for assessing hydromorphic change. Very few studies have considered hydromorphic processes when designing flow operational policies for tropical dams. Studies of sediment connectivity are also either implicitly or explicitly dealing with issues of longitudinal connectivity, but not that in the lateral dimension. Both of these gaps were addressed in the current thesis.

Chapter Three addressed Objective (i). The chapter developed a framework ('HyFFlow') designed to provide a systematic characterisation of river flow regimes and applied this to the Baleh River. HyFFlow consists of four packages, together yielding information on rainfall and flow patterns that provides a comprehensive baseline against which future changes can be assessed. As well as indicating key low flow thresholds, their durations, magnitudes and timings, HyFFlow identified a number of distinct classes of high flow events (defined as 'Event Types') in the Baleh. These low and high flow statistics were later used (Chapter 5) to inform functional flow recommendations. HyFFlow analyses of historical data indicated subtle and complex changes to long-term hydro-climatological conditions in the Baleh catchment: (i) analyses of the hydrograph indicated that there have been reductions in flow in the wet season, but not at other times of the year, and (ii) while there is no evidence of long-term trends in precipitation across the catchment (no change in monthly rainfall values over a 51- year period), there has been an increase in the number of days each month with no rainfall in some sub-catchments. These temporal trends have implications for dam impacts and functional flow recommendations because they indicate that neither 'boundary conditions' nor flow recommendations should be seen as static. This is discussed further below in Section 6.3.

Chapter Four evaluated changes in connectivity across the Baleh catchment in response to the dam and associated changes in landcover and land use, and so addressed Objective (iii). Connectivity was assessed using the sediment connectivity index (IC), a model that quantifies structural connectivity using spatially explicit data on gradient and roughness across the catchment. IC models suggested that historical changes in landcover (most recent 20-year period) have not altered connectivity between the Baleh and the Rajang markedly. Differences in IC between the current and 2001 landcover were minimal. Future roads and forest clearance (of 10%) were predicted to have detectable impacts on connectivity between the Baleh and Rajang, with small decreases and increases in IC respectively. However, models suggested that once the dam is built, the effects of the impoundment on connectivity will swamp those of roads and landcover change, with a major portion of the Baleh becoming almost completely disconnected from the Rajang. In addition, operation of the dam will have implications for IC upstream of the dam wall because of how different lake levels (and hence the area of land inundated) alter connectivity. Larger lake areas impact IC most, so managing water levels in ways to reduce changes in connectivity is suggested as a possible way of controlling the dam's impacts on connectivity in the upper basin. The Baleh is a large dam, with an estimated land area of more than 500 km^2 flooded at the highest anticipated lake level. Accordingly, changes in connectivity associated with this inundation affect a large area.

Chapter Five addressed Objectives (ii) and (iv) and provided insights into the potential effects of regulated flow regimes on sediment entrainment and hydraulic conditions in the Baleh River. The basic operational mode of the Baleh dam will be to release water from four of its five turbines as continuously as possible. The modelling work presented in this chapter found that, operating in this mode, flows equating only to four or five turbines are unlikely to result in appreciable entrainment of coarse bed material (i.e. material at respective site D_{16}, D_{50} and D_{84} sizes). These flow magnitudes are less than the natural high flow events defined as part of HyFFlow, and so over time, in the absence of significant bed entrainment and transport of material, the bed could be expected to become progressively armoured and coarser, as seen in dammed rivers worldwide. However, the modelling indicated that with the contribution of flows by downstream tributaries from adjacent sub-catchments to the mainstem, appreciable entrainment of bedload transport can be expected when these tributaries are at higher flow (respective Q10 values). Chapter 5 also looked at how flow magnitude and water stage affect hydraulic habitat heterogeneity and exposure of the gravel bars present at some sites. This analysis used velocity coefficient of variation as an index of heterogeneity, and the modelling results indicated lower discharges resulted in relatively high values of habitat heterogeneity. Thus, low flows that occur naturally in the river, rather than negatively affecting habitat, appear to help support greater heterogeneity at certain times of the year. These low flows also expose gravel bars, supporting a habitat matrix that consists of both wet and dry areas.

6.3. Sustainable Management of The Baleh River and Its Catchment

6.3.1. Impacts of HEP and The Need for Functional Flows

Objective (iv) was to design specific flow recommendations to help guide operation of Baleh Dam. This requires an understanding of the likely consequences of the regulated flow regime on the Baleh's hydrology, hydraulics, and sediment dynamics. This understanding was generated through the work completed as part of Objectives (i)-(iii).

Dam construction and the planned HEP operation will drastically reduce peak flow magnitude in the Baleh and alter temporal patterns of variability (Lum, unpublished MRes thesis). HyFFlow and the analyses presented in Chapter 5 indicated that flows regularly exceed 2000 m^3/s, and often more than 3000 m^3/s in the natural river. The mean magnitudes of the three types of natural event were 1000 m^3/s for Type A, 2000 m^3/s for Type B and 2500 m^3/s for Type C. The SWAT modelling indicated that post impoundment flows may rarely exceed 1000 m^3/s at the dam site, and for much of the year sit at less than 500 m^3/s (496 m^3/s, 4 turbines).

These changes could potentially have a number of effects. They may affect fish spawning (Carmichael et al., 1998) or other aspects of fish habitat suitability, and may increase bank erosion downstream (Hupp et al., 2009) as a result of the hungry water associated with sediment trapping by the dam. Lum (unpublished MRes thesis) estimated that around 95% of the river's sediment load will be trapped behind the dam, with profound implications for habitat in the downstream river. The specific functional flow recommendations provided in Chapter 5 were designed to minimise the effects of these changes on the river by specifying operational requirements in terms of flow magnitude, timing, and duration. In doing so, Objective (iv) of the research was addressed.

Geomorphology provides the physical template that acts as a mediator between flow and ecological processes (Meitzen et al., 2013). Despite this, geomorphic processes are rarely considered or modelled explicitly when developing functional flows (Batalla, et al., 2021). Most functional flows are retrospective, designed to restore, recover, or improve river structure or function. This requires scientists and managers to establish the degree of departure from the natural state (i.e. the new regime state), and understand the causal mechanisms responsible for departure from the natural state. While this is quite different to the Baleh, which is yet to be regulated, what is common is the fact that functional flows need to identify components of the hydrograph that provide a distinct geomorphic or ecological function so that these can be built these into an operational regime (Yarnell et al., 2015).

Flow variability can be simplified into the two ends of the flow range - high and low flows. Published work shows that managing floods or high flows to ensure ecologically effective discharges (i.e. magnitude and frequency of specific flows) and available sediment supply is necessary for maintaining persistence and habitable conditions in dammed rivers (Topping et al., 2010). On the other hand, low flows are vital in aquatic ecosystems as they shape the habitat heterogeneity (Yarnell et al., 2006; Palmer et al., 2010). During low flow periods, channels become narrower and shallow, reducing flow velocity, and causing sediment deposition. This creates shallow water patches and heterogeneous substrate areas which are important habitats for aquatic species (Bowen et al., 2003). Low flows also contribute to the formation of pools and riffles, which support diverse aquatic organisms (Yang, 1971). They also create isolated habitats that act as refugia for species during high flow events, providing a critical habitat for sensitive species (Magoulick and Kobza, 2003). Maintaining natural low flows is thus essential for promoting long-term persistence of aquatic species and preserving habitat heterogeneity.

The complexity associated with sediment supply sources, transport, and deposition dynamics represents the greatest challenge for implementation of functional geomorphic flows (Topping et al., 2010). Many organisms show preference for specific substratum and bar morphologies, yet these conditions can be highly dynamic in space and time. Sediment transport and depositional dynamics can drive spatial shifts in substratum materials, hydraulic conditions, habitat heterogeneity, and biological communities (Pritchett and Pyron, 2011). As outlined in Chapter 5, the flow recommendations for the Baleh have been designed to mitigate these concerns by incorporating specific low and high flow magnitudes, duration and frequencies.

Functional flows have been suggested as a means to enable adaptation to environmental change (Yarnell et al., 2015). As detailed in Chapter 3, there were subtle and complex changes to long-term hydro-climatological conditions in the Baleh catchment (Chong et al., 2021). There have been reductions in flow in the wet season, and an increase in the number of days each month with no rainfall in some sub-catchments. The river ecosystem may already be changing in response to these hydro climatological drivers. One way of seeing this is to say that if functional or environmental flows are designed to best match or mimic natural parts of the hydrograph, recommendations may need to be altered through time to reflect changes to rainfall and the river's unregulated hydrograph. However, we may alternatively see regulation as a way to help buffer the river from these external changes by maintaining key aspects of the hydrograph. This is an emerging paradigm and work is needed to illustrate how it can be operationalised.

The final objective (Objective (iv)) has been achieved by successfully providing specific FFs recommendations that are categorised into low and high flows (more details in Chapter 5). Low flow recommendations used the seasonal baseflow regime as **normal minimum flow recommendations**, ranging from 222 m^3/s to 408 m^3/s but vary across the year as a reflection of rainfall patterns. Based on patterns in the long-term data, these flows should last around 3 days with a frequency of at least 3 times per month during the wet season, and 2 times per month during the dry season. In other words, the target for normal operational flows requires 2 to 3 turbines. Some flexibility in flow releases from the dam should be permitted in May and October as these two months reflect transition of wet to dry and dry to wet seasons; depending on water availability and antecedent conditions, releases between 295 m^3/s - 314 m^3/s would be permissible. During excessively dry periods, flows can be allowed to drop below the normal target minimum flows. These lower values can be seen as **absolute minima**. It is suggested that season specific Q95 values can be used for these absolute minima - 143 m^3/s for the dry months, and 243 m^3/s for the wet months. These flows should not extend for a continuous period of more than 5 days, to match the natural duration of such events. Also, such low flows occur no more than 5 times per year, so dam operation should target no more than 5 such low flow episodes each year. For these flows, 1 to 2 turbines should be operated.

High flow recommendations that are potentially significant for sediment entrainment are based on the analysis of the long-term natural hydrograph of the Baleh along with the HEC-RAS® modelling of sediment entrainment. Natural event Types A and B could be recreated by artificial releases designed to mimic their shape. These events had rather clear seasonal patterns of occurrence, so releases could potentially be made to mimic their timing. Type A events contain individual floods with peak discharges that range from 463-1507 m^3/s at the dam site. Turbines can generate up to 620 m^3/s and if released when the downstream sub-catchments are wet, discharges of up to 1727 m^3/s could be created in the downstream river. Events of this magnitude allow for entrainment of coarser bed materials up to at least the median size. They last for around 20 days and most frequently occur in late May to early June, and then again in November and December; typically, they occur around 15 times per year. Type B represents very similar events to Type A in terms of duration but range in magnitude from 1347-2693 m^3/s at the dam site. These events tend to occur more commonly towards the end of the year (November and December), with frequencies of around 8 times per year. Artificial releases mimicking these events could also potentially be created by dam releases, carefully timed to coincide when downstream sub-catchments are at high flow.

6.3.2 Sediment Management Strategies

River management that focusses on the catchment scale is most effective if it takes landscape and channel connectivity into account, to interpret geomorphic and ecological recovery pathways (Brierley and Fryirs, 2009). Sediment connectivity is a critical aspect of river ecosystem health (Fuller and Death, 2018). Findings in Chapter 4 support an already extensive literature which shows that dams can significantly disrupt downstream sediment transport processes (i.e. longitudinal connectivity) causing downstream starvation. This starvation leads to a range of ecological impacts in downstream river sections, while the trapped material creates problems for dam operation, reducing dam and reservoir lifetime.

The value of the sediment connectivity results for the Baleh catchment lie in their role in being able to quantify the effects of various catchment changes that typically occur together but are rarely evaluated in ways that provide insights into how they interact. The results provided a first order approximation of how lateral connectivity in the Baleh may be affected by anticipated rates of forest loss and the construction of an access road to the dam, with these alterations then resulting in changes in connectivity between the Baleh and the Rajang. In the Baleh, consideration of sediment connectivity is important as the region is known for its high levels of rainfall and steep topography, which can lead to high rates of soil erosion and sediment transport.

The IC analysis of the road indicated some potential localised effects. This finding is similar to that reported in other studies (Llena et al, 2019), and suggests that some empirical work might be needed to more fully understand how the road will affect sediment delivery to the river channel. This is discussed more in Section 6.4.

IC modelling results also showed that different lake levels will influence the connectivity of hillslopes and channel (i.e. lateral connectivity), with higher lake levels causing greater connectivity/more accessible sediments. The Discussion section in Chapter 4 also mentioned that effective management of smaller sub-catchments with higher sediment connectivity is essential for maintaining the health and function of the river ecosystem. Other parts of the Baleh project are looking specifically at fine sediment to develop a sediment budget for the river and understand how this might be affected by impoundment. Once this fine sediment work is completed, it may be possible to integrate this with the IC modelling work to produce a sediment management plan for the catchment. Such a plan would also need to consider coarser material. Starvation of this material could be addressed either by sluicing or bypass channels for finer material. In some rivers, coarse material is placed downstream to help augment supply, but in the case of the Baleh, because many tributaries join and deliver sediment, this may not be necessary.

6.4. Future Work

The management of water resources requires a delicate balance between providing human needs for energy and water, and the preservation of natural ecosystems. Traditional management approaches have focused on the provision of a stable water supply, and as a result, many of the world's major rivers are now dammed (Maavara et al., 2020). This has led to significant ecological impacts downstream, stemming from altered flow regimes and disrupted sediment connectivity (World Commission on Dams, 2000). The concept of functional flows has grown out of the recognition of this issue, although alarmingly few examples of their application are found in tropical systems when set against the growth of tropical dams. The Baleh is therefore a significant case study to show what can be done, to build requirements into an operational regime in advance of dam operation. Ideally, the other functional flow components such as human needs, the biological (i.e. river ecology) and the thermal component (i.e. river temperature) will be integrated in the future to help improve the geomorphic and hydraulic flow recommendations for the Baleh provided in this thesis.

The recommendations are based on modelling work and essentially stem from predictions of the likely effects of the anticipated HEP regime; they are not based on empirical data on sediment dynamics nor how the channel has been affected by impoundment. It is therefore critical that once the dam becomes operational, changes in the river are monitored. Such monitoring can form the basis of adaptive management programme in the first 5-10 years of dam operation. It is another 3-4 years before the dam is scheduled to become operational, providing time to initiate monitoring and assessment pre-construction as well as planning longer term monitoring of post-dam changes. Specific recommendations for next steps and monitoring of the river once the dam is operational are as follows:

1. Dam operators should develop a decision support system based around hydrologic forecasting (combination of weather forecasts) and direct measurements of reservoir levels, precipitation, and river discharge. The system can be used to schedule the proposed functional flow releases based on water availability and downstream flow conditions.
2. There is a pressing need for research to understand the habitat requirements of some key or target species. As detailed at the beginning of this thesis, the reason for focussing on habitat provision via geomorphic functional flows was due to the absence of habitat criteria that could otherwise be used in identifying ecologically important flows. In the remaining time before dam completion, this work should be prioritised to help refine the flow recommendations using explicitly ecological criteria (e.g suitable hydraulic and sedimentary conditions for target species).
3. Thermodynamic models should be built to help assess the impacts of the dam on river temperatures and identify options for mitigating such changes. This work is already underway as part of another element of the Baleh project.
4. A programme of field monitoring should be implemented after dam completion to assess bedload transport and changes in suspended sediment. Evaluations of bed armouring should also be undertaken. Such data can be used to help assess whether the high flow recommendations need to be revised.
5. Monitoring of the effects of road construction to assess impacts on connectivity should be undertaken. This should in part be used to help validate predictions of the IC modelling (e.g. local effects up and downslope of roads) but also to understand impacts on the river because of changes in connectivity. Particularly where the road crosses tributaries and bridge construction has taken place, impacts of fine sediment runoff should be assessed.

6. An adaptive management framework (e.g. DRIFT; Arthington et al., 2003) should be adopted to ensure that information from the monitoring (i.e. 1-5 above) can be fed back to help revise the dam's operational regime.

6.5. Conclusions

Rivers and their catchments are fundamental to sustaining life and so dams have become extremely controversial in Sarawak due to population displacement and impacts on human livelihoods. While existing impoundments are likely to have had an impact on the physical and ecological integrity of Sarawakian rivers, evidence of this is extremely limited since hardly any suitably detailed assessments have been carried out. Malaysia lacks any legal framework or standardised requirements for setting functional flows, so most (perhaps all) existing dams are operated with little regard to downstream river systems. The work presented here for the Baleh is perhaps one small step to turning the tide. The fact that the work has been funded in advance of dam construction and by the hydropower company (SEB) testifies to greater environmental awareness and a change in mindset. The story of the Baleh is, however, only just the beginning, and ongoing research and monitoring is needed to support adaptive management and secure the integrity of the river for its ecosystems and the local communities that depend on them.

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