THE ENVIRONMENTAL PERFORMANCE OF VERNACULAR SKYWELL DWELLINGS IN SOUTH-EASTERN CHINA

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ABSTRACT

Chinese vernacular dwellings are low-energy buildings constructed before the advent of modern external services. No work has been published that incorporates an exacting assessment of the environmental performance of these buildings. The principal aim of this research was to investigate the environmental performance of Chinese vernacular skywell dwellings quantitatively and to establish a model of rigorous and comprehensive qualitative and quantitative research in this area. This was done by analysis of on-site measurements and computer simulation of the environmental performance of eight vernacular skywell dwellings in three villages in south-eastern China – Xidi, Zhifeng and Yuyuan. Environmental performance and building form are examined in relation to current knowledge of the social and economic life of the villages in the past centuries, and to the environmental comfort and the activities of present-day residents of the eight dwellings and other vernacular houses in the villages.

It has previously been noted that, in general, the courtyard/skywell of vernacular dwellings decreases in size with progression from northern China to southern China as the climate becomes warmer. However, the mean size of the skywells was found to differ considerably between the three climatically similar villages – large skywells were found in Yuyuan village, medium sized skywells in Xidi village and very small skywells in Zhifeng village. While physical factors were found to be important in determining house form; socioeconomic, cultural and security considerations were found to be strong influences as well.

The investigation of the natural illumination of Chinese vernacular dwellings conducted in this study was the first quantitative study of the distribution of natural light in these houses. Houses in the three villages were found to differ in their distribution of illumination according to local skywell form. In all three villages residents were found to take various actions to pursue satisfactory daylighting. Two patterns of daylighting isolux contour in skywell dwellings were identified and analysed.

The first comprehensive quantitative study of the thermal performance of Chinese vernacular skywell dwellings was conducted by on-site measurement and administration of questionnaires to residents. Residents of Xidi and Zhifeng were found to appreciate the coolness of their houses in summer, but residents of all three villages found their houses unacceptably cold in winter. The efforts made by residents to mitigate extremes of heat and cold appear to be important in ensuring their thermal comfort. Evidence was obtained that evaporative cooling had a substantial influence on the temperature in the skywells of dwellings in Xidi and Zhifeng villages. In addition to the buffering of temperature by thermal mass, evaporative cooling was found to further reduce the fluctuation in temperature inside the skywell and is likely to have been the main reason that the mean dry bulb temperatures inside the skywells in these villages were lower than the mean external dry bulb temperatures. It is proposed that evaporative cooling in skywells can be exploited even in humid conditions, because natural ventilation can ensure exchange of air between the exterior and the interior of the skywell.

Summer temperature/humidity data obtained in the most used spaces of skywell dwellings in the three villages were plotted on psychrometric charts and were examined in relation to the boundaries of predicted thermal comfort zones. The acceptability of thermal conditions in the dwellings that was predicted using this approach was very much lower than that reported by residents. Residents appear to be more tolerant of high humidity with the presence of natural ventilation. Such air movement is desirable to improve the thermal comfort for house occupants in hot and humid conditions.

LIST OF PUBLICATIONS

Lau, B. and Duan, Z.C. (2008) The Daylight Benefit Conferred Upon Adjoining Rooms by Specular Surfaces in Top-Lit Atria. *Architectural Science Review*, 51(3): 204-211

Duan, Z.C., Lau, B. and Ford, B. (2010) Environmentally responsive site planning and building design – A case study: Xidi village in southeastern China. In: *IAQVEC 2010 – the 7th International Conference on Indoor Air Quality, Ventilation and Energy Conservation in Buildings, New York, 15-18 Aug 2010* (oral presentation)

Duan, Z.C., Lau, B. and Ford, B. (2010) Low Energy Buildings – the Environmental Tradition in the Chinese Vernacular Dwellings. In: *SET2010 – 9th International Conference on Sustainable Energy Technologies, Shanghai, 24–27 Aug 2010* (oral presentation)

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NOMENCLATURE

AH: absolute humidity

CSA: cross-sectional area

CSWD: China Standard Weather Data

DBT: dry bulb temperature

DF: daylight factor

DF_m: mean daylight factor

$DF_{m,hall}$: mean of DF values that were calculated within the hall area

$DF_{m,sky}$: mean of DF values that were calculated directly under the skywell

$DF_{m,uti}$: mean of DF values that were calculated over the whole of the utility area

dT: apparent cooling effect of air movement

$E_{m,hall}$: mean of illuminance values that were measured within the hall area

$E_{m,sky}$: mean of illuminance values that were measured directly under the skywell

$E_{m,uti}$: mean of illuminance values that were measured over the whole of the utility area

Q_{cv}: convective heat flow rate

RH: relative humidity

T_n: neutral temperature

$T_{o.m}$: mean outdoor temperature of the month

UR: uniformity ratio

WBT: wet bulb temperature

WI: well index

1 INTRODUCTION

1.1 Objectives

Folk dwellings in the styles recognized as traditional in China were constructed from the Qin dynasty (established 221 BC) to the end of the Qing dynasty in 1911. In their numerousness and in the principles of design they express, they are of great importance in the history of Chinese architecture. By virtue of the era in which they were built, these dwellings are all low-energy buildings constructed at a time when energy-requiring external services could not be provided. The vernacular dwellings of China can be divided into eight types according to their plan and external form – courtyard houses, Hakka rammed earth houses, stilt house, overhanging houses, flat-roof houses, cave dwellings, tent dwellings and watch towers (Lung, 1991).

The courtyard house is the most numerous and most widely distributed type of traditional Chinese dwellings. Because of regional differences in landforms and climate, local materials, traditional building techniques and methods of construction, defensive requirements, religious traditions and disparities in economic conditions, courtyard houses take different forms in different parts of China. In south-eastern China, due to the dense population, the historically great economic prosperity, the particular security requirements of certain villages, and the hot and humid climate, multi-storey houses with high gables and a relatively small and compact courtyard evolved from the design of the basic courtyard house. This type of open space is termed the skywell.

Certain aspects of traditional Chinese houses have been studied extensively – aspects such as historical development, taxonomy, design features, and metaphysical concepts embodied in their design. However, little work has been done on the environmental performance of Chinese folk dwellings. The principal objective of the work described in this thesis is to investigate the qualitative and quantitative relationships between environmental performance and the building forms of traditional Chinese skywell houses through the study of folk dwellings in three villages in south-eastern China – Xidi, Zhifeng and Yuyuan. Environmental performance and building form are examined in relation to current knowledge of the social and economic life of the villages in the 17^{th}–20^{th} centuries, and to the environmental comfort and the activities of present-day residents of these traditional houses.

The spatial concept and environmental delight of traditional Chinese house design are a valuable inheritance that should be investigated, adopted and re-developed to suit contemporary design requirements. There is little published information on the quantitative environmental performance of Chinese vernacular dwellings with skywells. The aim of the research described in this thesis is to add to current understanding of the environmental performance of Chinese vernacular dwellings, and to establish a model of rigorous and comprehensive qualitative and quantitative research in this area. This research could be of great value in the conservation of these historically important buildings. Any design measures employed in the creation of these buildings that are intended to minimise energy requirements and ensure environmental comfort could be considered for use in practical building design today. It is hoped that this project will promote the reintegration of China's contemporary architectural culture with its architectural heritage.

1.2 Research questions

The following research questions were considered in this project.

1) What is the typical dwelling form in each village studied?

2) What is the architectural relationship between the geographical location, climate and social background of a village, and individual dwellings?

3) Are any features common to the individual dwellings in each village? What are the differences between dwellings in different villages?

4) How comfortable are the residents of these vernacular dwellings in respect of temperature, illumination and humidity?

5) How good is the environmental performance of skywell dwellings, as assessed by rigorous quantitative analysis of daylighting and thermal performance in summer and winter?

6) How do residents achieve thermal comfort in summer and winter?

7) What environmental benefit is conferred by the skywell?

1.3 Methodology

The methodology used to accomplish this research is described in this section. Three typical villages in south-eastern China were chosen – Xidi village (29.9°N 118°E), Zhifeng village (29.28°N 117.67°E) and Yuyuan village (28.77°N 119.66°E). Two or three typical dwellings within each village were investigated in detail.

The reasons for choosing the three villages investigated in this project were as follows:

- They are typical Chinese traditional villages with original architectural characteristics which are conserved in larger numbers and in better condition than in some other places.
- Obtaining permission to study the buildings was found to be easier in these villages than in some others.
- They are located in a similar climatic zone, enabling results from the three villages to be compared reliably.

A total of 8 houses were investigated in detail – the Yingfu dwelling, the Dunren dwelling and the Lufu dwelling in Xidi village; the Panmaotai dwelling and the Panxianxiong dwelling in Zhifeng village; and the Yufengfa dwelling, the Gaozuo dwelling and the Shuting dwelling in Yuyuan village. These dwellings were chosen because they are representative of the traditional dwellings in their villages, and because permission to study them was successfully obtained from the house owners.

1.3.1 Qualitative analysis

- Subjective study, photographs and observations
- Questionnaire-based research – a questionnaire was used to collect information from local people who have lived in traditional houses for a long time (see appendix A).

Photographs and observations

Photographs of the interior and exterior of Chinese vernacular dwellings and general views of the villages were taken during the on-site measuring periods. These images were shown in Chapters 3 and 4 to complement the other forms of information obtained in the study of the three villages.

Questionnaire

A questionnaire concerned with the daylighting and thermal performance of vernacular skywell dwellings was developed. This was for the collection of residents' views of the living conditions they experience in these vernacular dwellings, and for the assessment of comfort level in respect of illumination, temperature and humidity. Responses were obtained from adult occupants of traditional dwellings in the three villages studied – the questions were presented and explained to respondents in a short interview, and replies were recorded in writing by the present author since many of the interviewees had received very limited education. Respondents included, but were not limited to, some of the occupants of the eight dwellings studied in detail. Replies were obtained from 34 residents in Xidi village, 28 in Zhifeng and 30 in Yuyuan villge. In the questionnaire, interviewees were required to give responses to various questions on a scale of one to five, with five being the most positive score, one the most negative, and three a neutral score. The mean score was calculated and used as an index of the mean satisfaction with or strength of feeling concerning various aspects of the internal environment of the dwellings in the three villages.

1.3.2 Quantitative analysis

- On-site measurements were obtained, comprising building dimensions and climatic data on illuminance, air temperature, air humidity, surface temperature and air speed within and outside the dwellings studied.
- Computer simulation using Ecotect 5.50 (Autodesk, United States, http://usa.autodesk.com/) was used for quantitative analysis of solar conditions.

On-site measurements

Winter data collection in the three villages took place from 29th December 2008 to 19th January 2009 and from 7th February 2009 to 20th February 2009, summer data collection took place from 1st August 2009 to 30th August 2009 and from 28th August 2010 to 10th September 2010. Various measuring equipment were used to measure the site and building dimensions (laser ruler and tape measure), illuminance level (4-in-1 multi-function environment meter), air temperature and humidity (Gemini data loggers), wind speed (thermal and vane anemometers) and surface reflectance (photometer) surface temperature (infrared thermometer). These equipments are listed in appendix B. The procedures used in the various forms of on-site measurement are described in detail below.

1) Building dimensions

Dimensions of the eight dwellings studied were obtained using a laser ruler and a tape measure as the first step in carrying out the site monitoring. Obtaining the dimensions of the buildings enabled computer simulation to be carried out and provided a basis for the creation of drawings upon which environmental data could be displayed. The measured survey of these buildings provides a valuable record of this heritage.

Due to the complexity of the buildings' construction and the limited time available on site, not all dimensions of the dwellings were measured on site using the laser ruler; other measurements were obtained from photographs after the site visits. A 1 m stick painted in alternate black and white 20 cm divisions was used as a reference ruler. This reference stick was placed vertically or horizontally against the surfaces from which measurements need to be obtained (figure 1.1). *Enface* photographs of the surfaces of interest were taken in which the 1 m stick was present and dimensions were calculated as (length of unknown dimension in image / length of graduated stick in image) * real length of graduated stick (1 m).

Figure 1. 1 Reference stick attached to the wall that needs to be measured

The dimensions thus obtained were incorporated into detailed drawings of the eight dwellings created using the software AutoCAD 2008 (Autodesk, United States, http://usa.autodesk.com/). The drawings are shown in appendix C. Using AutoCAD, site plans of the three villages studied were also drawn using Google Earth 5.0 images showing the village layout (Google Inc., United States, http://www.google.co.uk/intl/en_uk/earth/); the contours of the hills surrounding the villages obtained from the website of the Shuttle Radar Topography Mission (SRTM) (http://www.dgadv.com/srtm30/); the layout drawings of Xidi village (Duan *et al.*, 2006), Yuyuan village (Chen, 2007) and Zhifeng village (Gong, 1999); and measurements taken on site in the present study.

2) Daylighting level

To carry out the quantitative analysis of daylighting performance of Chinese vernacular dwellings, illuminance testing was carried out using a 4-in-1 environment meter. The external illuminance level of the overcast day was measured first before inside measurements were taken. In principle, the external illuminance should be measured from a space without any obstacles such as a roof top. Since this was impractical, sky illuminance was measured from large open spaces (village squares). Having obtained an external illuminance value, the corresponding internal values within a given room were obtained within 1 minute. The present author was the sole field worker in this part of the study, and it was necessary for him to obtain sets of measurements by moving from the external measurement point to the room as quickly as possible. Ideally, internal and external illuminance values would have been obtained simultaneously, by using a pair of field workers; however, illuminance values under overcast days are generally stable, and while the slight separation in time of the external and internal measurements is a source of error, this is likely to have been minimal. Error was reduced further by taking at least 3 complete sets of illuminance measurements in each room, with each set preceded by a measurement of external illuminance; the mean of the three values for each internal or external point of measurement was taken to represent the daytime illuminance at that point under overcast conditions.

Horizontal illuminance readings at a height of 1000 mm above floor level were recorded from each floor of the dwellings. For each floor an approximate grid of measurements was obtained in each of the three sets of measurements. Measurements were obtained from points which were spaced evenly between columns – the columns were arranged symmetrically in all the dwellings studied. After processing of illuminance data, daylighting contours were generated using the software package Surfer 9 (Golden Software Inc., USA, http://www.goldensoftware.com/). The daylight distribution within the eight dwellings studied is shown in detail in chapter 5.

3) Air temperature and relative humidity

Air temperature and humidity within the dwellings were recorded using data loggers (Gemini Data Loggers, UK, http://www.geminidataloggers.com/). This is to obtain data for the quantitative analysis of thermal performance within Chinese vernacular dwellings. Data loggers which had been set to record the dry bulb air temperature (DBT) and relative humidity (RH) every minute were placed in the skywell, the hall and a bedroom of each house. Data loggers were placed at an approximate height of 1.5 m (data collected at this height are more meaningful because it could best represent the zone in which people's activities take place). For comparison in each village the DBT of air outside the dwellings was measured by placing a data logger on a flat roof of a contemporary building near the studied vernacular dwellings, to record the microclimate of the village. Data collected by this reference data logger was then compared with that collected within the dwellings. Data loggers located in skywells and rooftop were protected from sunlight and rain (figure 1.2), while those placed inside the buildings were placed on items of furniture. DBT and RH were recorded continuously over seven days in summer and winter measuring periods in the eight houses studied. In this study, external air temperature or external DBT indicates the temperature recorded on the roof, which is the external temperature used for comparison against internal temperature. Data were exported to Excel through the software of Tinytag Explorer 4.7 (Gemini Data Loggers, UK, http://www.geminidataloggers.com/software/tinytag-explorer). A summary of the data is given in section 6.3

Figure 1. 2 Data loggers in skywells or on roof tops were protected by a curved cover

4) Air velocity

Air velocities below 2 ms^{-1} were measured using a thermal anemometer. This type of instruments was mainly used inside dwellings. Higher air speeds were measured using a vane anemometer. This type of instrument was mainly used to measure outdoor wind speed and wind speed in the main entrances of buildings. Air speed data were used to examine the mode of ventilation within the skywell dwellings and its effect.

Air speeds inside and outside the eight dwellings studied in detail were measured in the summer testing period. Only two airflow measuring instruments were available and there were many openings in which measurements could be obtained (the main entrance, the secondary entrance, and internal and external doorways to annexes). For each measurement point other than the main entrance, air velocity measurements were taken simultaneously with measurements at the main entrance, so that measurements at other locations had a common reference. Measurements were taken by continuous manual recording over a period of 10 minutes; means of these values were used for analysis. This was done at least three times for each pair of measurements. Replicate measurement periods were not contiguous. Unless otherwise stated, all air velocity measurements were made in the daytime. Mean air speeds at locations other than the main entrance were expressed as proportions of the air speed at the main entrance at that time, to enable non-concurrently obtained measurements of air speed at locations other than the main entrance to be compared. The mean air velocities at different locations in each of the eight dwellings as a proportion of mean air velocity in the main entrance measured at the same time are shown in appendix D.

5) Surface temperatures of dwellings

The internal and external surface temperatures of the eight vernacular dwellings were measured by an infrared thermometer. Surface temperature data were used to determine the rate of convective heat flow through the surfaces of the dwellings.

In each dwelling, temperature of the external surface of the wall and the surrounding surfaces of the skywell (the inner surface of the skywell wall, the surface of the skywell floor, the inner surface of the roof and the wooden panel lining) were measured at least three different times a day from morning to late afternoon on different days. For each surface at each time of measurement, temperatures were obtained at several measurement points that were distributed evenly. The mean value of these measurements was then taken as the temperature of that surface.

6) Surface reflectance

The surface reflectance of vernacular dwellings was measured by a photometer using a method described by Tregenza and Loe (1998). In this method, a sample of a material having known reflectance η_r, is used as a reference. According to Tregenza and Loe (1998), good quality white A4 paper has a reflectance of about 0.9. After testing the luminance of a particular surface material of a vernacular dwelling, the result was recorded as L_s. The reference (A4 paper) was placed in the same position as the surface previously measured, and tested; the result was recorded as L_r. The reflectance of that surface, η_s, would then be calculated using the following equation.

$$\eta_s = \frac{\eta_r \ L_s}{L_r}$$

This procedure was carried out two or more times for each surface material, using readings taken at different points on the surface of the material. Each pair of material / white paper readings was obtained at a different point on the material's surface. Mean values of surface reflectance were derived from the individual values of surface reflectance calculated at the different points. The number of pairs of building surface / paper readings varied according to the exposed area of a particular surface material. It ranged from 2 (for smaller exposed areas) to 6 (for larger exposed areas) readings.

Computer simulation

In this study, data of all types could only be collected on site for limited time during measuring periods, so it was not possible to obtain solar radiation data throughout the year. Nor would it have been possible to assess the solar conditions of whole villages on site because there were no suitable vantage points, or to study the external illumination of buildings in isolation because of the density of construction in the villages. To overcome these limitations, solar radiation was studied primarily using Ecotect 5.50 (Autodesk, United States), a software package for the modelling of a range of environmental characteristics of buildings, and preexisting solar radiation data. Other forms of weather data were used in modelling as well. The different forms of computer simulation carried out in the project are described below.

Weather data were obtained from EnergyPlus database (EERE, 2011); within EnergyPlus, China Standard Weather Data (CSWD) obtained from the weather stations closest to each of the villages were used, since none of the villages contained a weather station. The complete CSWD datasets and details of the creation of these datasets are given in China Meteorological Bureau, Climate Information Center, Climate Data Office *et al.* (2005). Within CSWD, typical year data derived from several years' unmodified weather data were used. The site study locations and the weather stations from which weather data were obtained are listed in table 1.1.

Table 1. 1 Locations of villages where study was conducted and the locations from which the weather data were obtained

locations of villages studied	location of nearest weather station
Yuyuan village (119.662°E, 28.77°N)	Qu Xian (118.867°E, 28.967°N)
Zhifeng village (117.67°E, 29.276°N)	Jingde Zhen (117.2°E, 29.3°N)
Xidi village (117.992°E, 29.906°N)	Tunxi (118.25°E, 29.75°N)

For convenience, in the remainder of this thesis, weather data obtained from the weather stations nearest the three villages studied will be described as weather data for those villages. Detailed climate information of the three villages can be found in appendix E (p319).

In the three kinds of simulation the parameters used were weather data from EnergyPlus, local topographic data, building dimensions, and default values for the properties of construction materials within Ecotect. In the simulation of direct solar radiation into the skywell void, data from the summer period (1st Jun – 31st Aug) were used.

1) Simulation of solar conditions within the three villages

It is impossible to observe the solar penetration to the whole village on site, so computer simulation had to be applied. Ecotect software was used to construct three-dimensional models of each village and its surrounding topography. The models were used to simulate solar exposure of and penetration to the village at the summer solstice, the winter solstice and at equinoxes, from sunrise to sunset, with the assumption of a clear sky condition all day.

2) Direct solar radiation into the skywell void

The amount of solar radiation which penetrates into the skywells of the eight studied dwellings was calculated using weather data from EnergyPlus, and Ecotect software. Using site measurement data, three-dimensional models of the eight skywell dwellings were modelled in Ecotect before carrying out the simulation. Use of computer simulation allows longer periods to be considered than would have been possible with on-site measurement.

3) Effect of mutual shading

In order to evaluate the effect of mutual shading in summer, the Yingfu dwelling in Xidi village was taken as an example. Indirect solar gain (the heat obtained through solar radiation incident on opaque surfaces) of the Yingfu dwelling was simulated using Ecotect software and climate data from Tunxi weather station. The house was modelled in Ecotect both as an isolated building and as a structure surrounded by the immediately neighbouring buildings present in Xidi village.

Thermal comfort criteria

In this study, in order to evaluate the summer thermal comfort provided by the skywell dwellings, temperature / humidity data obtained at 1-minute intervals throughout the daytime (06:00-18:00) of the one-week summer recording period for the most occupied spaces were displayed on the psychrometric charts. On each chart the boundaries of the thermal comfort zone with still air assumed are shown with a black line. These boundaries and the underlying temperature / humidity contours were plotted using Ecotect. In setting the boundaries of thermal comfort zones Ecotect applies conditions specified by Sayigh and Marafia (1998); these authors evaluated several studies in which researchers have attempted to create empirically derived chart methods for predicting and assessing the thermal comfort of buildings. The conditions are:

- To set boundaries of temperature comfort zone, use the expression $T_n = 17.6 + 0.31T_{o,m}$, where T_n = neutrality temperature and $T_{o,m}$ = mean outdoor temperature of the month. This is a refinement by Auliciems (1981) of an equation by Humpherys (1978).
- At 50% RH the width of the comfort zone is $T_n \pm 2°C$
- Upper and lower AH limits are 12 gkg^{-1} and 4 gkg^{-1} (from ASHRAE Standard 55-81)
- RH in thermal comfort zone must not exceed 90% (i.e. 90% RH contour of chart must be a boundary of the thermal comfort zone if zone is in contact with that contour)

In constructing the psychrometric charts residents were assumed to be sedentary. Having defined thermal comfort zones on the psychrometric charts in which still air was assumed, thermal comfort zones were also defined in which air movements affording natural ventilation were assumed to occur. On the basis of on-site measurements, air speed in skywells was taken to be 1 ms^{-1}, and those in halls and bedrooms were taken to be 0.2 ms^{-1}. The assumed air speed value is only for showing the effect of air movement on occupants' thermal comfort. On each of the psychrometric charts the boundaries of the thermal comfort zone with cross ventilation operating is shown with a red line.

In the present study the adaptive comfort model rather than the Fanger model was used for evaluating the thermal comfort in Chinese vernacular dwellings. The reasons for doing so were as follows:

1 The PMV model is based on data from artificial climate chambers. Such data lack contextual factors which have been shown to be important in determing thermal comfort, and which are considered in the adaptive model (factors such as building location, climate, and the attitude and experience of building occupants). Chinese vernacular skywell dwellings are all free-running buildings that have been occupied for hundreds of years. Traditions and expectations that influence residents' experience of these buildings have arisen and solidified in this time.

2 In the PMV model, occupants are only considered as passive recipients of thermal stimuli presented by the artificial climate (de Dear, 2004), while in the adaptive model, occupants interact with and adjust to their environment (de Dear and Brager, 1998). In the Chinese vernacular dwellings considered in the present study, residents were seen to use various measures to make themselves comfortable, such as changing their clothes, moving to shaded spaces, opening doors, and using small fans in summer.

3 As noted previously, building occupants are more tolerant of conditions if they have more opportunities for control open to them (Leaman and Bordass, 2000). As stated in 2 above, residents of the vernacular skywell dwellings investigated were found to take action to improve thermal conditions for themselves. These measures widen the range of comfort temperatures in their houses, and were taken into account in the analysis.

The boundaries of the comfort zones to be plotted in psychrometric charts can be generated by using a number of software, such as Climate Consultant 4.0 (EERE, USA, http://www.eere.energy.gov/), PsycPro (Linric Company, USA, http://www.linric.com/) and Ecotect (Autodesk, United States, http://usa.autodesk.com/). By using the adaptive thermal comfort model, the boundaries of the comfort zone generated by the different types of software are very similar (for example, in Climate Consultant the equation $T_n = 17.8 + 0.31T_{o,m}$ is used compared to the equation actually used in the study: $T_n = 17.6 + 0.31T_{o,m}$). This and the familiarity of the author with Ecotect were the reasons for the use of Ecotect to generate thermal comfort zones within buildings in this study.

1.4 Outline of the thesis

The thesis is divided into eight chapters.

Chapter 1: Introduction. The background, objectives and the seven research questions considered in this thesis are presented in this chapter. The methods to accomplish the research and to answer the research questions are described in detail. The thesis structure is also described.

Chapter 2: Literature review. A discussion of the previous research done by Chinese and western scholars on Chinese folk dwellings is presented in chapter 2; this account includes a description of the seven main types of Chinese traditional house as well as the adaptation of the different house forms to the different regional climates.

Chapter 3: Environmental context of the three villages. Studies of three villages – Xidi village, Zhifeng village and Yuyuan village – are set out. Background information on the three villages, their microclimates and basic building types are described and investigated qualitatively and quantitatively. The solar penetration to the three villages is simulated through Ecotect modelling. Research questions 1 and 2 are answered.

Chapter 4: Observation of eight dwellings. A total of eight houses were observed and investigated in detail: Yingfu dwelling, Dunren dwelling and Lufu dwelling in Xidi village; Panmaotai dwelling and Panxianxiong dwelling in Zhifeng village; and Yufengfa dwelling, Gaozuo dwelling and Shuting dwelling in Yuyuan village. Basic information about these dwellings, including building dimensions and photographs is presented in chapter 4. The locally distinctive features common to the individual dwellings in the three villages are identified; and research question 3 is answered.

Chapter 5: Daylighting performance. The daylighting data for the eight skywell dwellings obtained in the study are described and analyzed in detail. The daylighting distribution patterns of the eight dwellings derived from illuminance data collected on site are presented. Research questions 4 and 5 in respect of daylighting performance are answered.

Chapter 6: Thermal performance. The thermal data for the eight skywell dwellings obtained in the study are described and analyzed. The thermal environment of the skywell is discussed in detail with respect to several heat inputs and outputs – radiative heat gain/loss, conductive heat gain/loss, convective heat gain/loss, evaporative heat loss, and heat gain from internal sources. Research questions 4 and 5 in respect of thermal performance are answered.

Chapter 7: Thermal comfort in skywell dwellings. Thermal data recorded in the skywell dwellings in the summer measuring period are plotted into the psychrometric chart though the use of Ecotect software to evaluate the summer thermal comfort provided by the skywell dwellings. The measures that the residents take to achieve thermal comfort in summer and winter are also described. Research question 6 is answered.

Chapter 8: Conclusions. Using results from the field measurements, the environmental performance of Chinese vernacular dwellings with skywells is reviewed and conclusions are derived. The main contributions of this research are summarized. Research question 7 is answered.

2 LITERATURE REVIEW - CHINESE TRADITIONAL DWELLINGS

The forms of Chinese folk dwellings vary throughout China due to differences in geographical features and climate, local materials, defensive requirements, economic conditions and the influence of religious factors. Chinese people have lived in houses of these designs for hundreds of years. They are all low-energy buildings created without external services at the time of construction. In this chapter, Chinese folk dwellings are classified; the features that save energy and provide maximum environmental comfort in different types of Chinese vernacular house are identified; and a summary of previous research on Chinese folk dwellings will be presented. A detailed review of existing research into Chinese vernacular dwellings by Chinese and western scholars is shown in appendix E (p319).

2.1 Classification of Chinese folk dwellings and their adaptations to different climates

Chinese traditional dwellings can be divided into eight types according to their plan and external form - Hakka rammed earth houses, stilt houses, overhanging houses, flat-roof houses, cave houses, tent dwellings, courtyard houses and watch towers (Lung, 1991). Figure 2.1 shows the distribution of Chinese traditional houses within the different climatic zones in China. Regional differences in Chinese folk dwellings arise from differences in landforms and climate, local materials, traditional building techniques and methods of construction, defensive requirements, religious traditions and disparities in economic conditions. Rapoport (1969) explored the determinants that shape dwelling form in his classic text and pointed out that house form is not simply determined by physical forces (climate, materials and technology and site) or any single factor; instead, socio-cultural forces play a primary role while the climatic conditions, methods of construction, materials availability, and the technology modify its form.

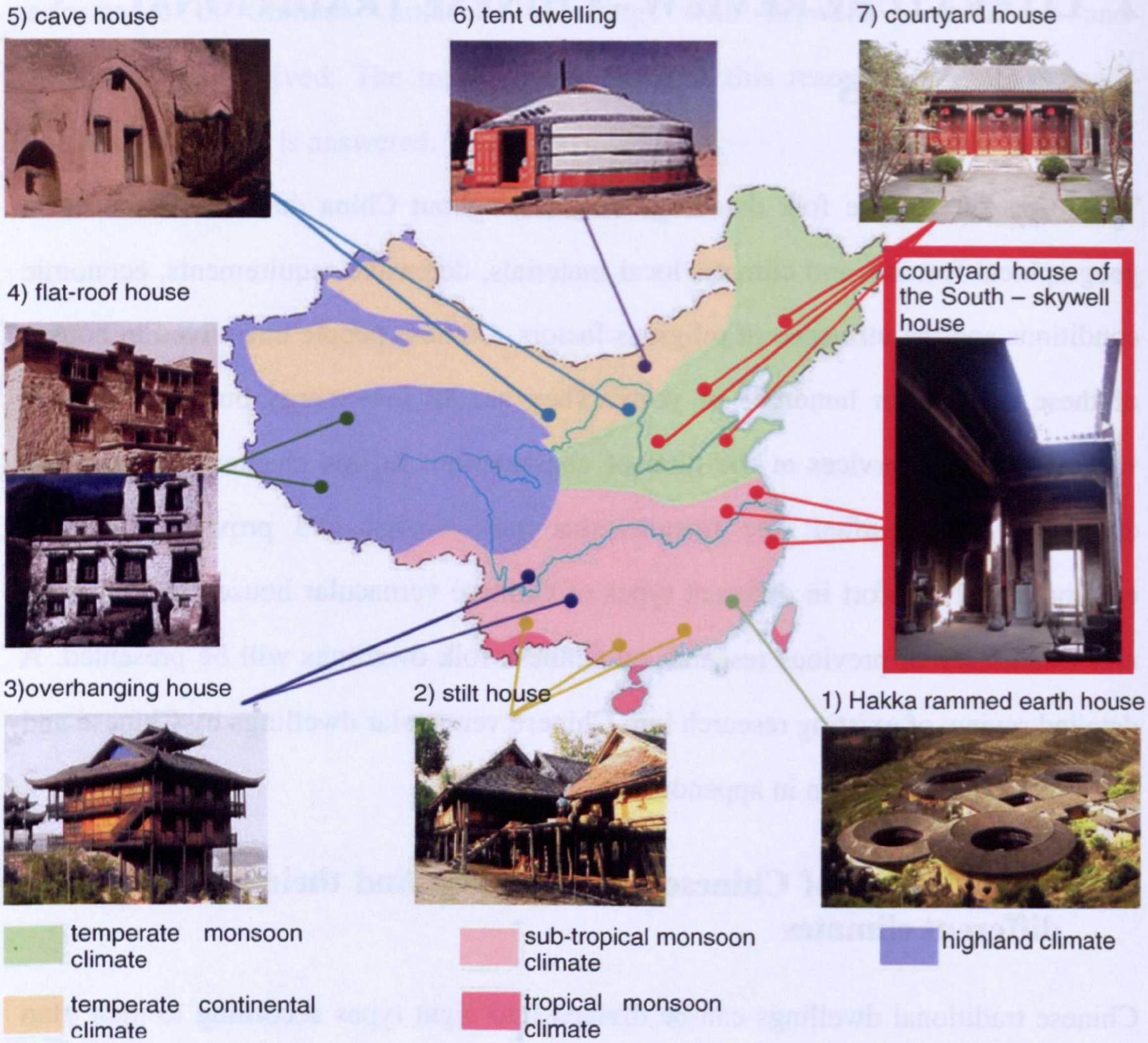


Figure 2. 1 Distribution of Chinese folk dwellings across different climatic zones in China (adapted from Duan *et al.*, 2010)

In this section, several categories of traditional dwelling associated with regions of China are considered. Proceeding clockwise round a map of China, the categories are: (1) Hakka rammed earth houses, (2) stilt houses, (3) overhanging houses, (4) flat-roof houses, (5) cave dwellings, (6) tent dwellings and (7) courtyard houses (figure 2.1). Each type of Chinese folk dwelling will be introduced, as well as the adaptation of the different house forms to the different regional climates. Where environmental design features are present in these dwellings, the aim of these features is to provide residents with the greatest possible comfort in respect of temperature, humidity, daylighting and air movement while using the minimum of humanly-generated energy. These features are discussed below. The watch tower is excluded from this account because this type of building is mainly used for defence and storage, and not normally for habitation. The courtyard house is described at greater detail because it is the most common type of Chinese folk dwelling, being distributed extensively in China; and because the courtyard house of southern China is the subject of the present study.

In this section, psychrometric charts showing monthly means of daily minimum and maximum temperatures at different locations are presented to indicate the climatic conditions of those areas.

2.1.1 Hakka rammed earth houses

The rammed earth houses (figure 2.2) in Fujian province of southern China have a unique architectural form – they are fortress-like round or rectangular buildings with a large courtyard in the middle, and consist of many individual dwellings. The walls are made of yellow rammed earth mixed with rice slurry, lime, sand and stone, and the eaves are topped with grayish black roof tiles (Knapp, 2005). Rammed earth house are 3-6 storeys high and can accommodate 300 – 500 residents. The form of Hakka rammed earth houses is dictated by the possibility of communal violence and the requirements of the cooperative clan system in this region (Lung, 1991).

Figure 2. 2 Hakka rammed earth house (Source: Wikipedia, 2011)

Fujian has a sub-tropical monsoon climate; it experiences hot summers (mean temperature above 27.2°C) with abundant rainfall and warm winters (mean temperature above 12°C), and a high relative humidity throughout the year (figure 2.3). There are often typhoons between June and September. The main thermal requirement of houses in this region is to prevent overheating in summer.

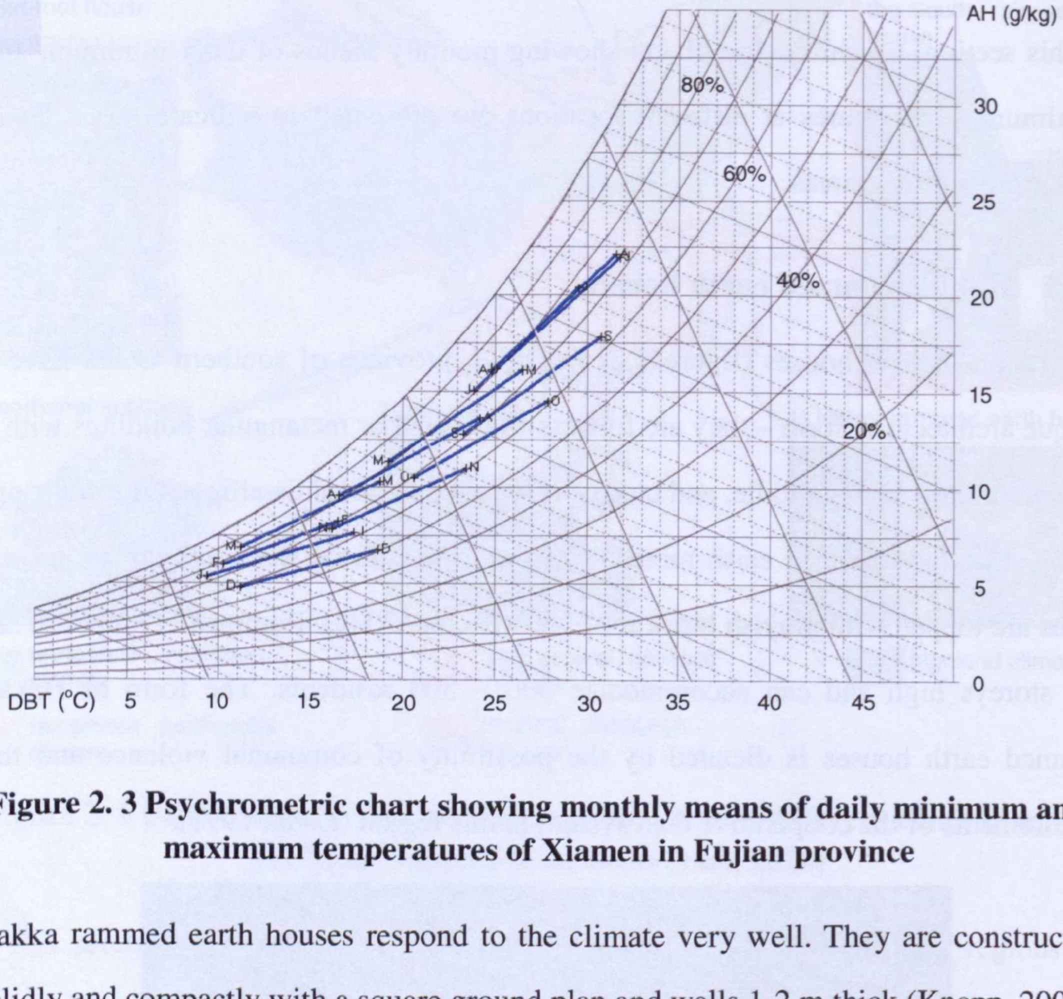


Figure 2. 3 Psychrometric chart showing monthly means of daily minimum and maximum temperatures of Xiamen in Fujian province

Hakka rammed earth houses respond to the climate very well. They are constructed solidly and compactly with a square ground plan and walls 1-2 m thick (Knapp, 2005). The walls are mainly composed of fresh earth, which is readily obtainable within a short distance of the settlement. With high heat capacity, the walls absorb heat during the summer day and release it during the night. This improves the comfort of residents by keeping the internal temperature lower than the external daytime temperature. Exterior openings are limited, both as a defense measure and to avoid excessive sunlight in summer – ground floor windows are absent or quite small, while upper story openings are larger. Rooms on the upper floor, where there is more daylight, are used as bedrooms; while the kitchens and storage rooms are located on the bottom floor. The roof eaves overhang by more than 1.5 m to exclude much of the intense solar illumination in summer, especially from the larger openings on the upper level. According to Huang (1994), the earth house progressed from a square to a circular ground plan. In Huang's view this might be because, for a given volume, the round earth house has the least surface area exposed to the sun, and because round shapes are more resistant than other shapes to strong winds.

2.1.2 Stilt houses

Stilt houses (figure 2.4) were constructed by a minority people in the southernmost part of China. The living space of the stilt house is raised about 2 m above the ground. This space is supported by wooden or bamboo stilts that are produced abundantly in the far south of China (Lung, 1991).

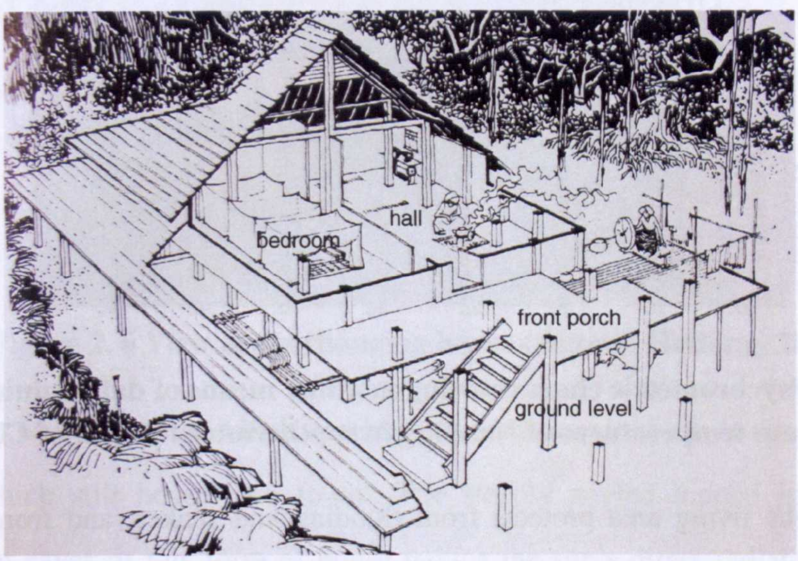


Figure 2. 4 View of stilt house (Source: Knapp, 2005)

The houses are rectangular and include a hall, a bedroom, a front porch and an open ground level where the supporting stilts are exposed. The two levels are connected by a wooden ladder. Stilt houses are small and cannot accommodate large families. This is because in the tradition of the minority people in the region where stilt houses are found, children are required to leave the parental home on attaining adulthood (Lung, 1991). There is almost no furniture in the living space; residents sleep on mats on the floor (Lung, 1991).

The southernmost region of China has a subtropical monsoon climate with hot summers, warm winters, abundant rainfall and high humidity. In the city of Nanning in Guanxi province the maximum summer temperature is above 32°C and the average winter temperature is above 14°C (see figure 2.5).

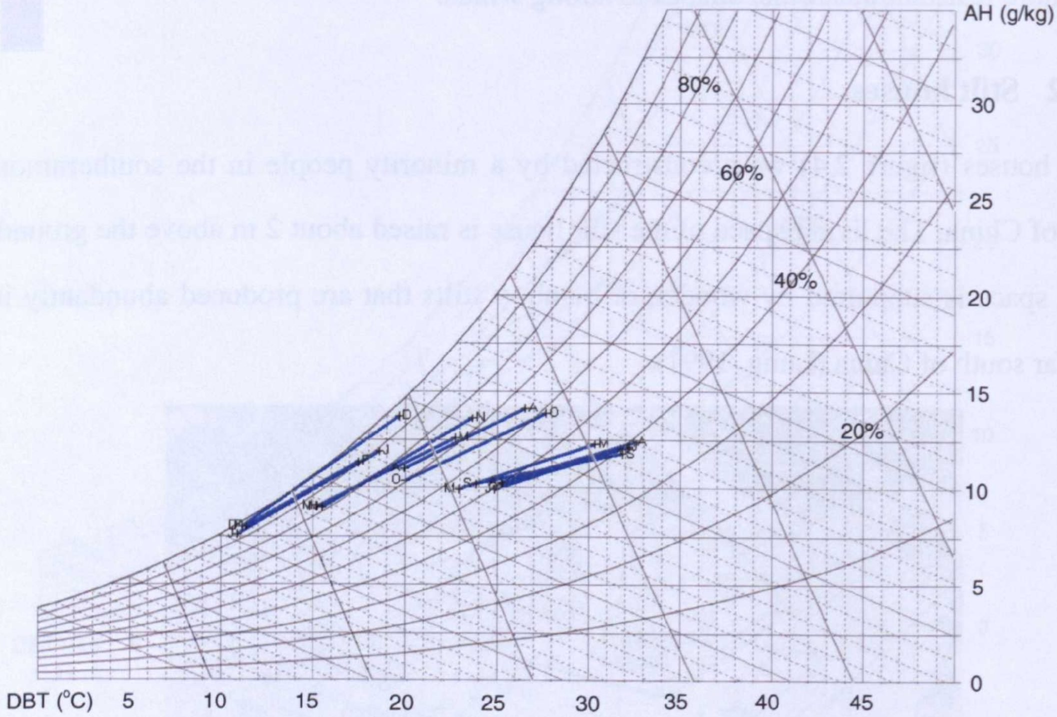


Figure 2. 5 Psychrometric chart showing monthly means of daily minimum and maximum temperatures of Nanning in southernmost region of China

Elevation of the living area protects from flooding and snakes, and from humidity through ventilation. The open, stilt-level area of the house is the coolest part of the house during the summer daytime. The houses have large porches and steep overhanging roofs which shield the dwellings from intense sunlight and rainwater (Knapp, 2005).

2.1.3 Overhanging houses

Overhanging houses are mainly found in the hilly areas of Sichuan and Guizhou in the south-west of China. This type of dwelling is an adaptation of the stilt house that conforms to the requirements of the local terrain, and is usually built on slopes and river banks (figure 2.6). The overhanging house design secures maximum living space on a hilly topography and minimizes construction costs. The structure is stable because most of the structural load is transferred to the ground and only a small load is imposed on the stilts (Lung, 1991).

Figure 2. 6 View of overhanging house (Source: Hudong, 2009)

The climate of the areas in which overhanging houses were built is similar to that of areas in which stilt houses are found. The steeply angled hipped roof and deep overhanging eaves of this form of house reduce the sun's direct radiation and allow rainwater to run off freely.

2.1.4 Flat-roof houses

Flat-roof houses are mainly found in Tibet which is in a plateau region that is more than 4000 m above sea level. In this region, there are many high mountains and deep gorges but very few flat surfaces for the houses to spread out horizontally. Therefore, they are built three to four storeys tall (Knapp, 2005).

The external walls are built with stones and have few openings. A typical flat-roof house with four storeys is shown in figure 2.7. Livestock are kept on the ground floor; the winter room is on the first floor, while the summer room is on the second floor. The top storey incorporates a worship hall and a drying space (Knapp, 2005).

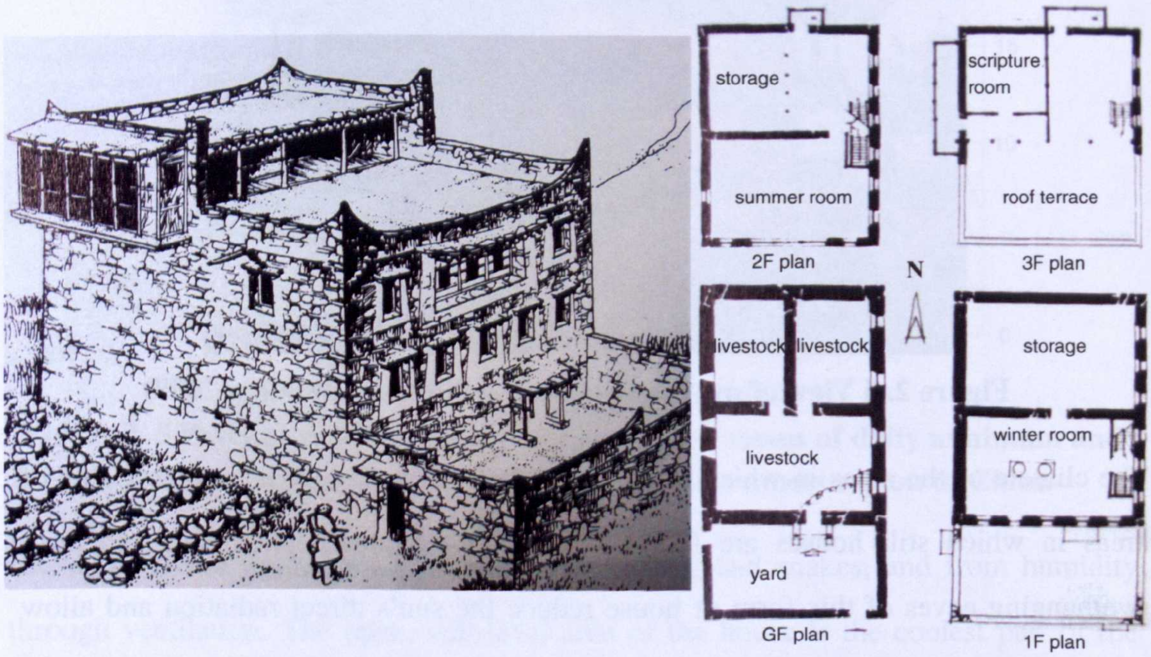


Figure 2. 7 Plan and view of flat-roof house (Source: Knapp, 2005)

Tibet's plateau climate has a long cold winter and a short warm summer (figure 2.8). Rainfall is limited and the region is dry, especially in winter. The traditional flat-roof houses that were built in this region have some features to provide warmth in winter.

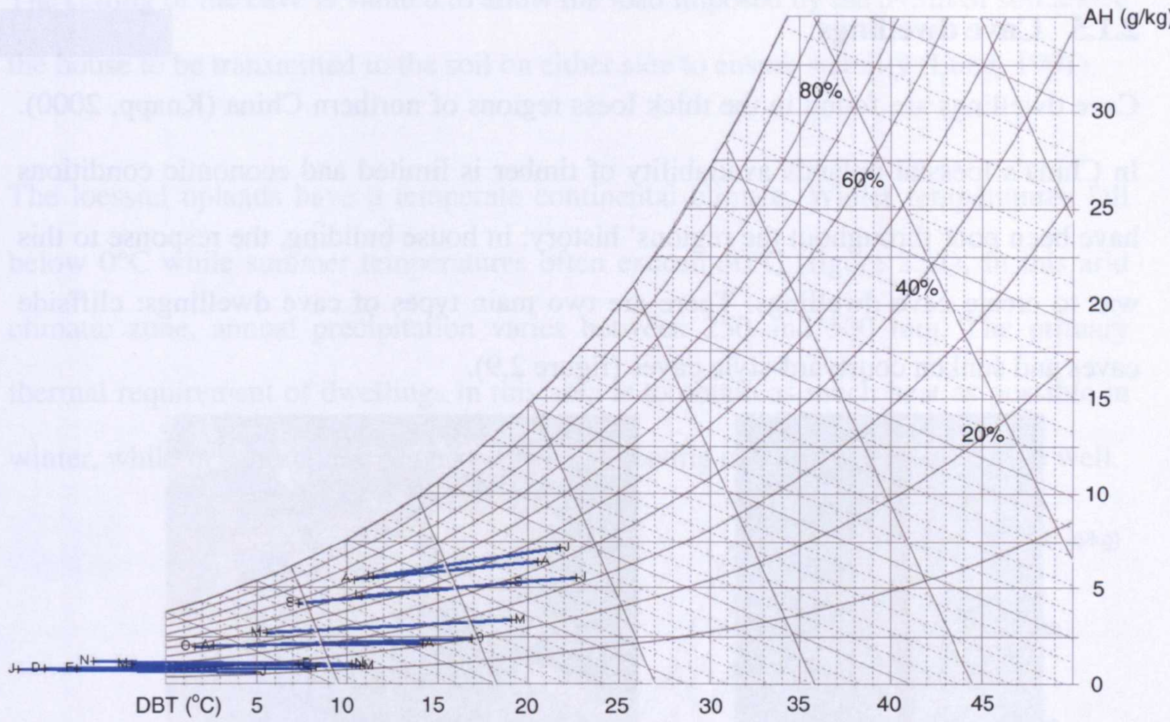


Figure 2. 8 Psychrometric chart showing monthly means of daily minimum and maximum temperatures of Lhasa in Tibet

Animal pens in the ground level of the dwelling provide security, and heat from the warm bodies of cattle, sheep and horses warms the structure. The winter room has thick walls and is windowless on the northern side (see figure 2.7). It is insulated on the northern side by a storage area for grain, which protects against the bitter northerly prevailing winds. The winter room also has five south-facing and three east-facing windows to obtain sunlight during the coldest season. It also has a stove, which warms the room during cooking. This room serves as a bedroom and activity room for residents in winter. The summer room is directly above the winter room; it is the summer living area, and has windows on three sides to enhance ventilation. The roof is flat in order to capture as much sunlight as possible and to provide a large amount of space for drying food and other activities (Knapp, 2000). Due to the limited rainfall, the flat roof does not present problems with drainage. Thick snow in winter also adds to the thermal insulation of the roof.

2.1.5 Cave dwellings

Cave dwellings are found in the thick loess regions of northern China (Knapp, 2000). In China's loessial uplands availability of timber is limited and economic conditions have been poor throughout the regions' history; in house building, the response to this was to create cave dwellings. There are two main types of cave dwellings: cliffside caves and sunken courtyard-style caves (figure 2.9).

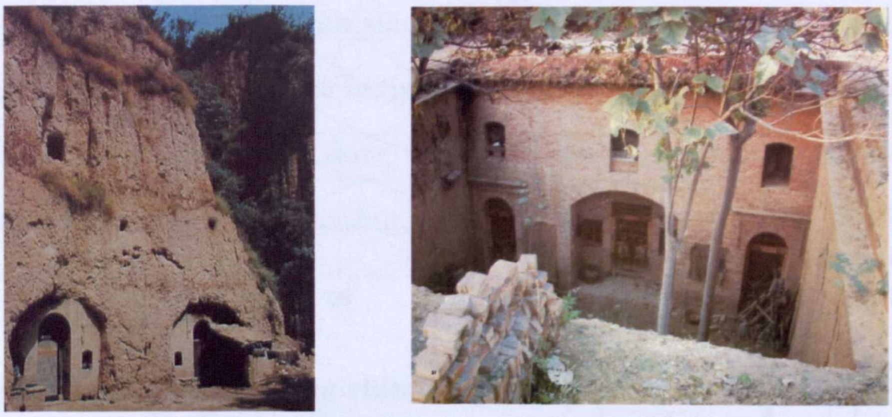


Figure 2. 9 Cliffside cave (left) and sunken courtyard cave (right) (Source: Lung, 1991)

Cliffside caves are dug from the loess cliffs, while sunken courtyard style caves are built where there is no cliff. In sunken courtyard style caves the head of the household lives in the northern part of the house (e in figure 2.10), while the children live in the west and east (c in figure 2.10). Kitchen and store space are in the southeast (b in figure 2.10), while the toilets and livestock are in the south.

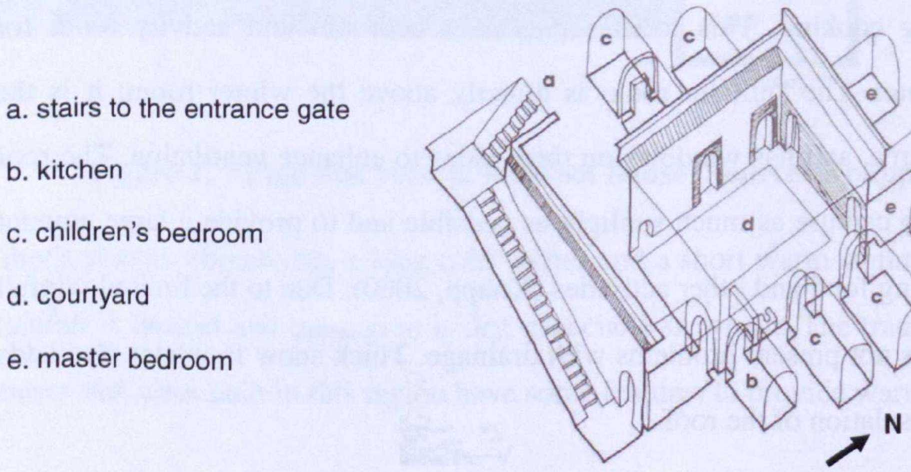


Figure 2. 10 Axonometric view of courtyard cave (Source: Lung, 1991)

The ceiling of the cave is vaulted to allow the load imposed by the 3–5m of soil above the house to be transmitted to the soil on either side to ensure stability (Lung, 1991).

The loessial uplands have a temperate continental climate. Winter temperatures fall below 0°C while summer temperatures often exceed 30°C (figure 2.11). In this arid climatic zone, annual precipitation varies between 250 and 500 mm. The primary thermal requirement of dwellings in this area is to obtain as much heat as possible in winter, while in summer the prevention of overheating needs to be considered as well.

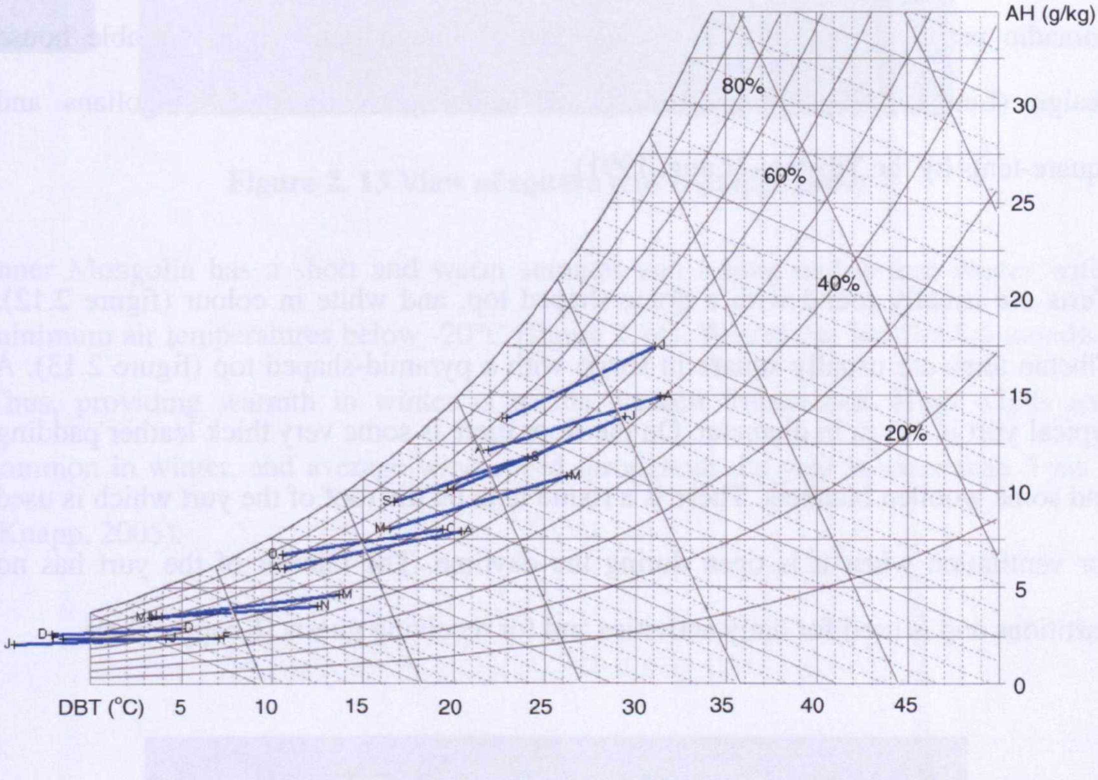


Figure 2. 11 Psychrometric chart showing monthly means of daily minimum and maximum temperatures of Xi'an in Loessial upland

Cave dwellings provide protection from the cold winter winds and the intense sunlight in summer. These houses exploit the thermal properties of the earth around them and are cool in summer and warm in winter due to the thick loess conserving heat very effectively. When the winter outside temperature is below 0°C, the temperature 4-6 m below ground in cave dwellings is still 14.5°C-16.5°C. During the hottest period of summer, temperatures inside the cave dwellings only range between 14°C and 15.5°C

(Hou *et al.*, 1989). Cave dwellings often have large hearths which are heated by burning wood and plant stalks; these serve as beds and sitting areas, and maintain warmth through the winter.

2.1.6 Tent dwellings

Tent dwellings are mainly found in Inner Mongolia, Tibet and Qinghai in the north-west of China, regions in which building materials are scarce but sufficient cowhides or sheep hides are available for the creation of shelters. They are used by nomadic peoples who move frequently and require a lightweight, portable house design (Lung, 1991). Tent dwelling are called yurts by the Mongolians and square-tents by the Tibetans (Lung, 1991).

Yurts are usually round with a dome-shaped top, and white in colour (figure 2.12). Tibetan tents are usually square in shape with a pyramid-shaped top (figure 2.13). A typical yurt is 4-6 m in diameter. On the floor there is some very thick leather padding and some woollen blankets. There is a round hole on the roof of the yurt which is used for ventilation when it is open during the daytime. The interior of the yurt has no partitions and is used for daily activities and for receiving guests (Knapp, 2000).

Figure 2. 12 View of yurt (Source: Hudong, 2010)

Figure 2. 13 View of square tent (Knapp, 2000)

Inner Mongolia has a short and warm summer and a long and severe winter with minimum air temperatures below -20°C (figure 2.14). Winter can last for 5-6 months. Thus, providing warmth in winter is of the greatest importance. High winds are common in winter, and average wind speed throughout the year is more than 3 ms^{-1} (Knapp, 2005).

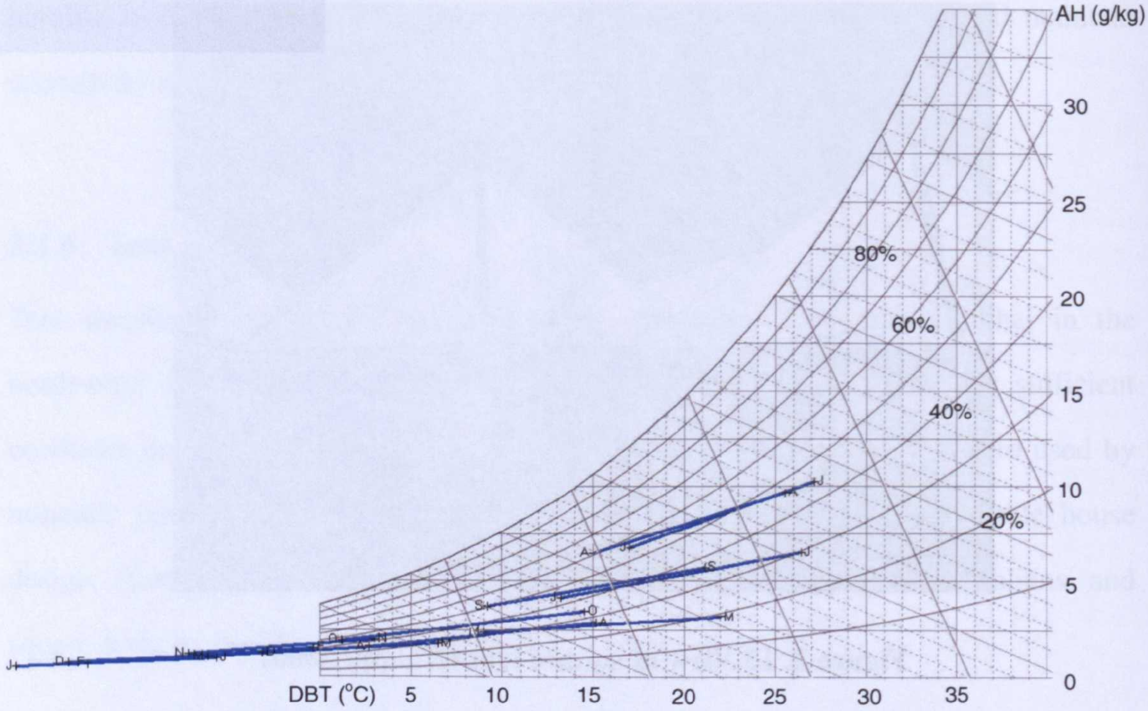


Figure 2. 14 Psychrometric chart showing monthly means of daily minimum and maximum temperatures of Hohot in Inner Mongolia

A yurt is covered with sheets of felt with various thicknesses. In summer, a single or double layer of felt is sufficient while in winter more layers of felt are added to enhance insulation and maintain warmth. Sometimes layers of sand are incorporated between the felt layers to retain additional warmth (Knapp, 2005). There is a hearth in the middle of the yurt for cooking, and to provide additional heat in winter. The round yurt deflects strong winter winds and blizzards efficiently.

2.1.7 Courtyard houses

Courtyard-style houses vary in detail according to climate, geographical location, social and economic conditions, and local architectural custom. The most typical form of courtyard house in the north of China is the one-storey 'four-in-one' courtyard house of Beijing (figure 2.15). (The core of the layout is a courtyard, with rooms around the skywell on four sides; hence the term four-in-one.) The courtyard houses in the south (figure 2.16) are mainly two- or three-storey houses with high gables and a relatively small and compact courtyard termed the skywell (Knapp, 2000).

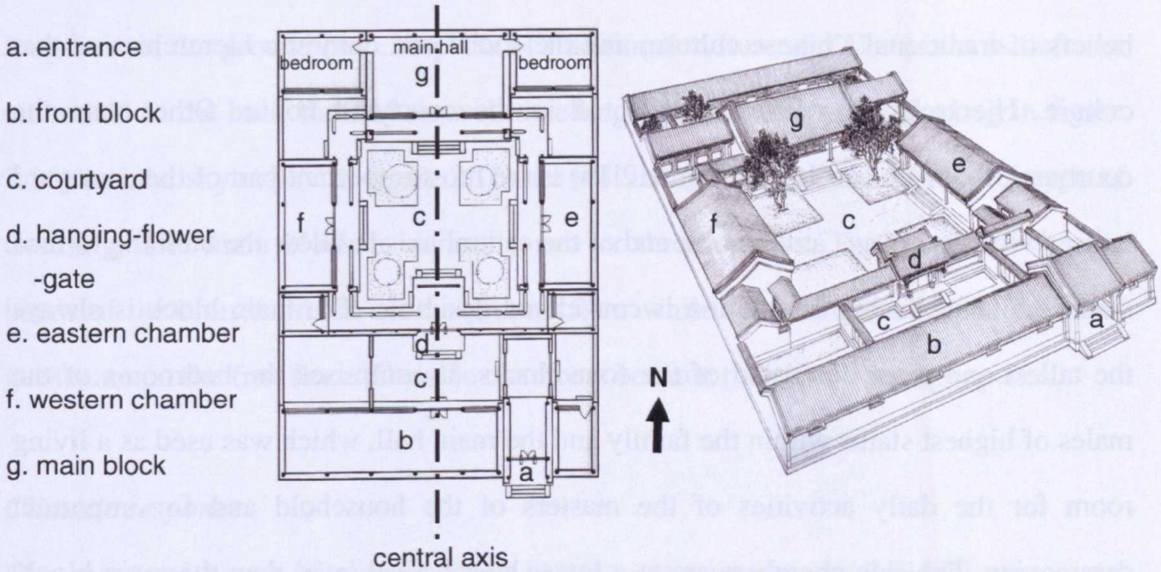


Figure 2. 15 Plan and 3D view of courtyard house (Source: Hudong, 2011)

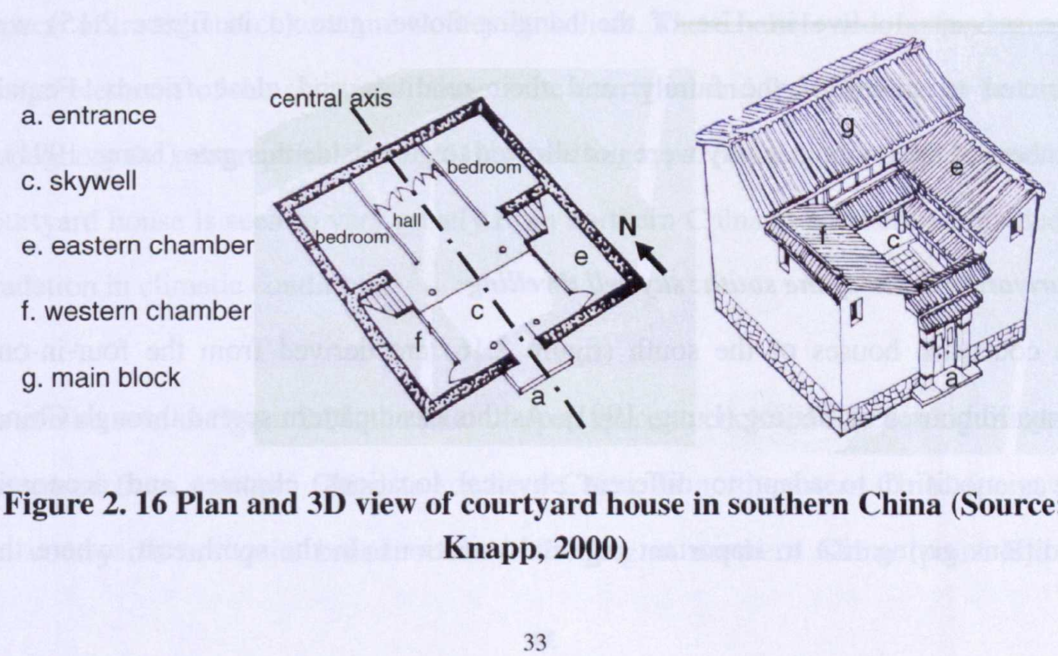


Figure 2. 16 Plan and 3D view of courtyard house in southern China (Source: Knapp, 2000)

Courtyard houses of Beijing

Rooms within the four blocks facing onto the courtyard are connected by corridors. The courtyard house is normally symmetrical with a north-south central axis (figure 2.15). The main entrance is situated at the south-east of the dwelling. The block to the south (b in figure 2.15) is the front block; the block to the north (g) is the main block. The blocks to the east (e) and the west (f) are the eastern chamber (bedroom) and the western chamber.

The house form of the courtyard dwelling reflects Confucian thought, the customs and beliefs of traditional Chinese culture, and the social and domestic hierarchies of that culture. Hierarchical orders are reflected in the courtyard house. Other than the courtyard, the main block (g in figure 2.15) is the most important part of the courtyard house, which is always at the north end of the central axis to allow the building to face south – a south-facing orientation is considered desirable. The main block is always the tallest and most decorated of the four blocks. It comprises the bedrooms of the males of highest status within the family and the main hall, which was used as a living room for the daily activities of the masters of the household and for important ceremonies. The side chambers are at a lower hierarchical level than the main block. They are the guest rooms or bedrooms for the children, while the front block is for male servants to live in. Use of the hanging-flower gate (d in figure 2.15) was restricted to males of the family, and their relatives and close friends. Female members of the owning family were not allowed to go outside this gate (Lung, 1991).

Courtyard houses of the south: skywell dwelling

The courtyard houses of the south (figure 2.16) are derived from the four-in-one courtyard houses of Beijing (Lung, 1991). As this basic pattern spread through China, it was modified to adapt to different physical locations, climates and economic conditions giving rise to important regional variations. In the south-east, where the climate was hot and humid, the economy more prosperous, available land scarce and the density of population greater than in other provinces, single-storey houses like the courtyard dwellings of northern China were not able to accommodate enough people in a given area and therefore multi-storey houses with small skywells were built (Ronald, 2005).

Just like a courtyard house, a skywell house is also usually symmetrical and rectangular in plan. The core of the layout is a skywell, with rooms around the skywell on three or four sides. The skywell and an open hall facing into the skywell lie on the long axis of the ground plan. Aspects of traditional culture and Confucian beliefs are embodied in the built form of skywell dwellings as well. The main block (g in figure 2.16) and the skywell (c in figure 2.16) are still the most important part in this type of dwelling. The main block is normally two or three storeys. The bedrooms for the heads of the household are on the ground floor while the bedrooms for children and guests are on the first floor. The side chambers became transit and storage spaces.

Climatic response

The courtyard house of eastern China is the most numerous and widely recognized type of ancient Chinese dwelling. The built form of the courtyard house embodies aspects of traditional culture and Confucian beliefs. These beliefs and the fundamental design elements of the courtyard house - the courtyard and the hall - are to be found throughout the geographical range of this dwelling type. None the less, the form of the courtyard house is seen to vary greatly from northern China to southern China due to gradation in climatic conditions.

As can be seen in figure 2.17, the ratio of open space to enclosed space is significantly decreased from northern China to southern China. In north-eastern China (point A), the courtyards are quite broad; while in Beijing in northern China (point B), the courtyards are still large but smaller than in the northeast, and transitional spaces (corridors) are present. In south-eastern China (point C), courtyards are greatly condensed. Here, the open spaces or cavities are quite small, and are termed skywells rather than courtyards. In the southernmost part of China (point D), the skywells are even smaller and more transitional spaces are present.

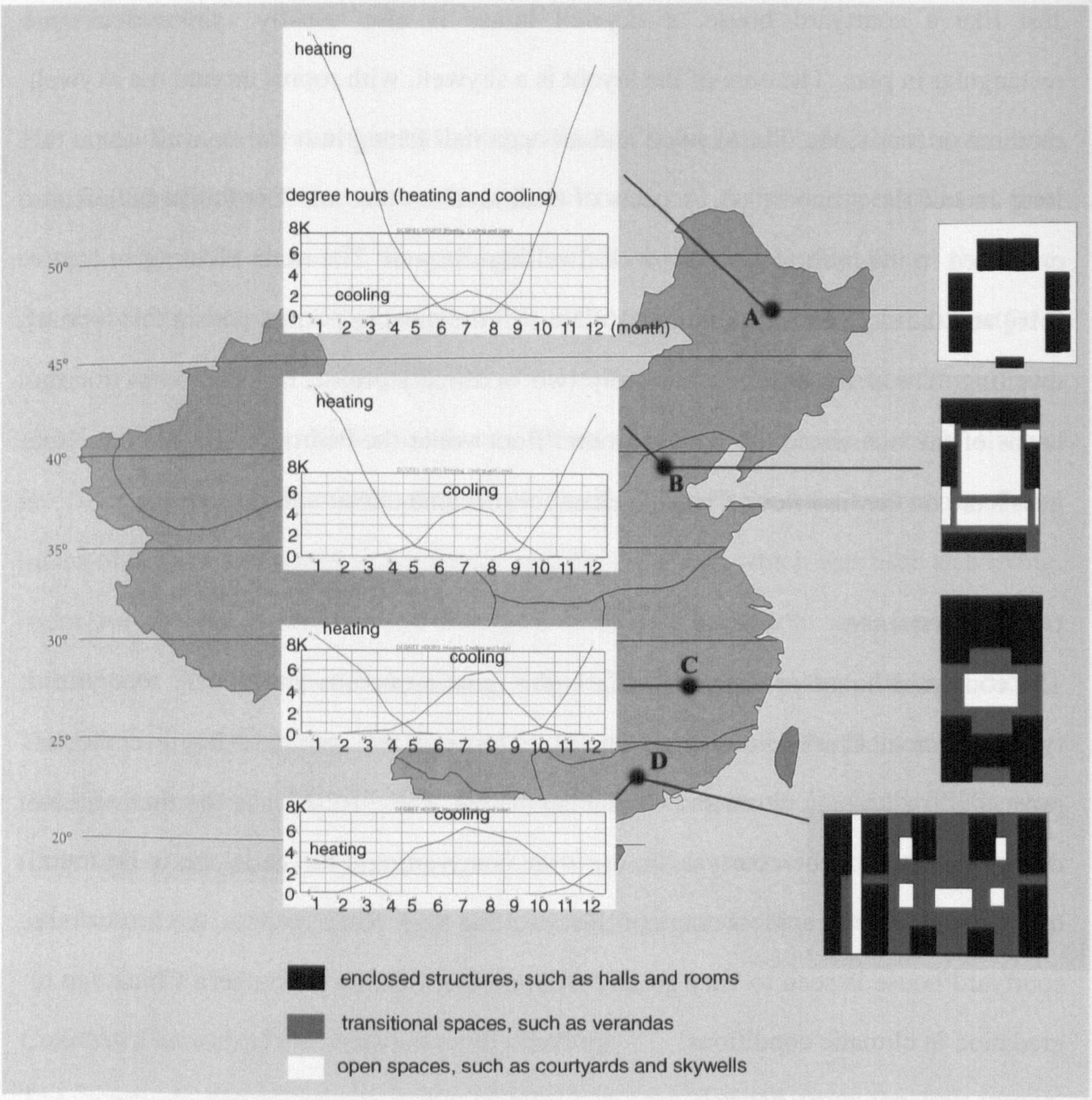


Figure 2. 17 Ratio of open space to enclosed space in ground plans of houses in different regions of China (adapted from Knapp, 2000)

Degree hour can be used as a measure of heating and cooling requirements of courtyard/skywell dwellings in the different regions. Heating and cooling degree hours of courtyard/skywell dwellings of different general plans associated with different parts of China are also shown in figure 2.17. Total degree hours of cooling or heating in one day is the number of degrees that the temperature is above or below a standard reference temperature multiplied by the number of hours in that day for which the temperature is above or below the reference value. Daily totals of degree hours can be summed for each calendar month to enable the changing heating and cooling requirements throughout the year to be studied. Hot weather in an area gives rise to a large total number of cooling degree hours, implying that considerable effort will be needed to prevent overheating in buildings. Conversely, a large total number of heating degree hours indicates colder weather, in which buildings will need to be heated. In figure 2.17, monthly totals for heating and cooling degree hours in different regions were calculated using climate data included within Ecotect.

The different proportions of enclosed structures, transitional spaces and open spaces are due to variation in climate. In north-eastern China, where the climate is dry and extremely cold in winter (the winter monthly total heating degree hours are over 20K), a large amount of heating is needed. The courtyard is relatively large in order to receive as much winter sunshine as possible when the sun's position is low. The walls are thick to reduce the loss of heat in winter, and large hearths are common. Northern China has cold winters, and hot summers so heating and cooling measures are both required. Courtyards are still large enough to obtain sufficient solar radiation in winter. The covered corridors provide shelter from the sun in summer and allow the sunlight to penetrate into the rooms in winter. The corridors also shelter residents from rain and wind when they walk from one room to another in bad weather.

In the hot and humid areas of southern China, cooling and dehumidification are of great importance. The open spaces in two- or three-storey dwellings become smaller while transitional spaces enlarge significantly. The small skywells prevent sunlight from penetrating the buildings and enhance the ventilation of interior spaces when the windows and doors are open in summer. However, with small skywells the solar illumination of the ground level will be inferior to that of the upper level. With the even hotter summer of the southernmost part of China, the skywell becomes a mere shaft to prevent excessive solar gain, catch passing breezes, and collect rain water.

In the following chapters, Chinese vernacular dwellings with skywells in south-eastern China (point C in figure 2.17) are considered in depth.

2.1.8 Summary

The design features of different types of traditional Chinese dwellings that meat local climatic demands, save energy, and provide maximum comfort are identified above.

Chinese traditional dwellings have been found to have low-energy characteristics, which are well suited to their environmental conditions. A low-energy building should make the greatest possible use of non-humanly-generated sources of energy. Its design should admit daylight, heat and air currents when they are beneficial and exclude them when they are not – thereby minimizing the house's requirement for electricity and combustible heat sources in securing environmental comfort for the occupants.

For those dwellings that are located in areas experiencing hot summers, the main priorities in temperature regulation are to minimize heat gain and to achieve cooling. To minimize heat gain from solar radiation houses incorporate features such as a deep overhanging roof, small external openings, transitional spaces (verandas) and narrow tall skywell. To minimize heat gain in hot summers many houses have large thermal mass, which is achieved by having thick walls of loess or masonry. To provide cooling potential and reduce humidity many houses (houses of the courtyard type) incorporate a skywell.

The main priority in temperature regulation for houses in regions experiencing severe cold is to minimize heat loss and maximize heat gain. To minimize heat loss houses have good insulation – such as tent dwelling – which is achieved by covering the dwelling with numerous layers of felt. To maximize heat gain houses employ a number of design features. Some have animal pens on the ground floor to provide heat. Many incorporate a stove and a large hearth in the winter living area. To minimize wind impact some house designs, such as yurts, incorporate round shapes to give a favourable aerodynamic profile.

2.2 Published work on Chinese Vernacular Dwellings

Chinese and western researchers have studied Chinese traditional dwellings for several decades. In the early stages of this research, individual dwellings were observed and photographed and then groups of houses in particular areas of China were surveyed and recorded: surveys included Liu Zhiping's survey of about 200 dwellings in Sichuan province in 1941(see appendix F, p327); work on Zhang Zhongyi's research on dwellings of Southern Anhui province in 1957 (see appendix F, p329); Zhejiang, Yunnan, and Fujian dwellings in 1984, 1986 and 1987 (see appendix F, p330); Beijing courtyard houses in 1996 (see appendix F, p331). In addition in the 1990s a nationwide photographic survey of Chinese folk houses was carried out (see appendix F, p332). In all these publications, accurate plans and sections were provided, and the structural and spatial elements of the dwellings were examined. Since the 1980s the aesthetic, historical, cultural, and geographical aspects of folk dwellings have been studied as well.

The study of individual dwellings is more meaningful if their surroundings are considered. Attention should also be paid to the village as the aggregation of individual dwellings. Huizhou villages were surveyed by China's Southeast University from 1992 to 1999 while more than ten ancient villages were studied by Chen Zhihua and his colleagues of Tsinghua University between 1990 and 2005 (see appendix F, pp332-333). In 2006, Duan Jin and his colleagues at Southeast University investigated Xidi village in the Huizhou area (see appendix F, p333). In the above books, the dwelling types, dwelling structure, building materials and decoration are described. Each village's historical background and development are summarized; the relationship between individual buildings and the whole village are investigated, and the factors affecting the evolution of folk dwellings and villages are examined.

Early studies of Chinese vernacular architecture were concerned with individual buildings or groups of buildings at a particular location. The first study of Chinese folk dwellings drawn from a wide territorial range was carried out by Liu Dunzhen and his colleagues in the 1950s. In their 1957 book, Chinese folk dwellings were classified into nine categories according to their plan and form. This is the first published categorization of types of vernacular dwellings. In Lung's 1991 book, houses were divided into eight types according to external form as previously noted. Lung described in detail each type's building plan, structure and building materials and other characteristics, and that building type's distribution in China. Jing Qimin published the book *Traditional Chinese Dwellings* in 1999 and a revised edition in 2007. In both editions the houses studied were assigned to one of Liu Dunzhen's nine classes, and the distribution of those nine types was examined. The classes were: circular dwellings (yurts) (most commonly found in Mongolian); longitudinal rectangular houses (primitive cave-dwellings) (most commonly found in Yunnan, North China and Central China); transverse rectangular houses (houses consisting of a varying number of rooms in a single line) (found throughout China); L-shaped dwellings (most commonly found in the countryside in southern China); three-in-one courtyard houses (most commonly found in Zhejiang, Shanghai and Yunnan); four-in-one courtyard houses (north-east China and Beijing); mixed of three-in-one and four-in-one courtyard houses (Jiangsu, Zhejiang and Sichuan); donut-shaped dwellings (Hakka rammed earth houses) (Fujian); and earth cave dwellings, (Henan, Shaanxi, Gansu and Ningxia) (Jing, 1999).

Among the different forms of Chinese dwellings, the courtyard house is distributed extensively in China and is the most common type of Chinese folk house (Lung, 1991). Courtyard-style houses vary in detail according to climate, geographical location, social and economic conditions, and local custom. The most typical form of courtyard houses in the north is the one-storey 'four-in-one' courtyard house. The courtyard houses in the south are mainly two- or three-storey houses with high gables and a relatively small and compact courtyard termed the 'skywell' (Lung, 1991).

The configurations of these skywell houses were derived from the four-in-one courtyard houses of Beijing, but their architectural style was modified to adapt to different physical locations, climates and economic conditions. In the south-east, where the economy was more prosperous and the density of population greater, single-storey houses like the courtyard dwellings of northern China were not able to accommodate enough people in a given area and therefore multi-storey houses were built.

The present study is concerned with the vernacular dwellings with skywells in south-eastern China and the environmental benefit conferred by the skywell in these houses is explored.

2.3 Research on the environmental performance of vernacular dwellings

As noted previously, existing published research on Chinese vernacular dwellings is largely concerned with the architectural culture, layout, form and structure of buildings, building materials and decoration, and the architectural setting and historical circumstances within which dwellings were constructed. However, less work has been done on environmental aspects of the traditional house.

Shi (2002) published an investigation of the use of environmentally benign materials in the construction of traditional houses in southern Jiangsu, Anhui and northern Zhejiang. This study was mainly concerned with the use of natural materials such as timber, bamboo, soil brick and tile in vernacular dwellings. The use of these ecologically sound materials in different parts of traditional houses, and inter-regional differences in their use, were examined (Shi, 2002).

In 2005 Huang Jihong, Zhang Yi and Zheng Weifeng published a study of the energy-saving techniques used in the construction in traditional houses in the Jiangsu and Zhejiang areas (Huang *et al.*, 2005). Through limited measurement of physical variables the authors obtained preliminary evidence of the importance of building form and structure in improving the internal environmental conditions of vernacular dwellings. They also gave details of the energy-saving techniques incorporated in the design including the insulation of walls, and the regulation of daylighting and solar illumination (Huang *et al.*, 2005).

A paper by Brian Ford, Benson Lau and Zhang Hongru entitled *The Environmental Performance of Traditional Courtyard Housing in China – Case Study: Zhang's House, Zhouzhuang, Jiangsu Province* published in 2006 is a valuable study of the environmental performance of a folk dwelling. The authors used field measurements of light, air temperature and air velocity in Zhang's House in Zhouzhuang Village near Shanghai to assess how this folk dwelling reforms in relation to the local climate. Zhang's house is a house with 'crab-eye' light wells – it has two narrow, rectangular-section light wells at the back corners of the house. Besides providing daylighting for the hall they adjoin, the light wells were found to improve ventilation in the house. The air speed of 0.1–0.3 ms^{-1} through the front of the hall increased to 0.7 - 1.2ms^{-1} through the doors adjoining the light well (Ford *et al.*, 2006). Control of glare in Zhang's house is also discussed – this is achieved by design of roof overhangs, colonnades and lattice windows, and by the planting of trees nearby (Ford *et al.*, 2006).

The above studies provide only semi-quantitative and anecdotal descriptions and analysis of the influence of building type, building materials, and method of construction upon environmental performance. It is difficult to evaluate accurately the thermal, daylighting and ventilation performance of vernacular houses on the basis of published work. There is a need for quantitative analysis of the internal environment of Chinese folk dwellings. An example of a quantitative study is Zhang Hongru's 2007 master's thesis *The Modern Application of Environmental Design Strategies from Vernacular Architecture in East China*. Through on-site monitoring and testing of physical models, the daylighting performance of the selected folk dwelling – Zhang's House in Zhouzhuang Village – was analyzed. The application of the principle of the crab's eye light well to an office building and two residential buildings in Shanghai was explored (Zhang, 2007). This thesis is a preliminary quantitative study of daylighting in a Chinese vernacular dwelling. Further quantitative studies of ventilation and thermal performance need to be performed in order to obtain more complete picture of the internal environment of the dwelling.

The principal aim of this research is to fill the research gaps in the current understanding of the environmental performance of Chinese vernacular skywell dwellings, and to develop a research methodology of rigorous and comprehensive qualitative and quantitative research in this area; since little work has been published that incorporates detailed on-site measurement of the environmental performance of these buildings.

3 ENVIRONMENTAL CONTEXT OF THE THREE VILLAGES

3.1 Introduction

Before investigating the environmental performance of Chinese traditional houses with skywells, it is important to identify the environmental contexts of these dwellings. This is because the dwellings are not isolated from each other or from their surrounding environments. Many dwellings being together formed a village although the village's location may be chosen first before the dwellings were built. Therefore, the geographical location, climate and social background of a village as the boundary of those dwellings need to be studied first. The physical geography, economic condition, basic building types and the site microclimates of the three villages – Xidi, Zhifeng and Yuyuan – will be described and investigated qualitatively and quantitatively in this chapter. Research questions 1 'What is the typical dwelling form in each village?' and 2 'What is the architectural relationship between the geographical location, climate and social background of a village, and individual dwellings?' will also be answered.

It is impossible to observe the solar penetration to the whole village on site, so computer simulation had to be applied. Ecotect software was used to construct three-dimensional models of each village and its surrounding topography. The models were used to simulate the solar exposure and penetration to the village at the summer solstice, winter solstice and equinoxes from sunrise to sunset, with the assumption of a clear sky condition all day.

3.2 Background of the three villages studied

3.2.1 Xidi village

The most representative type of dwelling is found in the region called Huizhou, near the Huang Shan Mountains. Xidi village (29°54' N 118° E) is a World Cultural Heritage Site in Huizhou area and has a history of over 950 years. It is located in Yi County, Huangshan City, Anhui Province (figures 3.1 and 3.2). There are still more than 200 ancient dwellings from Ming and Qing Dynasties, of which 124 are well-preserved. More than 350 families are currently living in the village, and its population is over 1000 (Duan *et al.*, 2006).

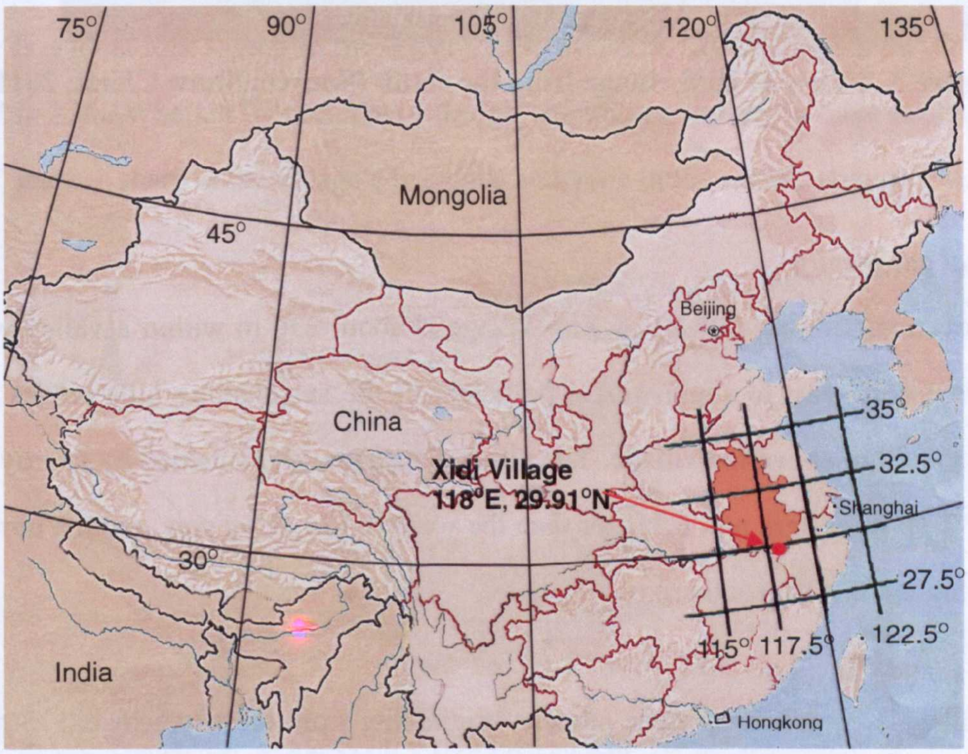


Figure 3. 1 Location of Xidi village (118° E, 29.91° N)

Figure 3. 2 View of Xidi village from the south (Source: Show China, 2011)

Physical geography

The elevation (from sea level) of Xidi village is about 230 m within a valley which runs from north-east to south-west. The height of the surrounding hills ranges from 120 m to 200 m above the village. The village is narrow and shielded by nearby hills (figure 3.3). Its eastern part is higher than the western low-lying part, and the northern part is higher than the southern part.

Xidi village is supplied by three streams originating from the northern hill. Streams pass through the village to the west, providing abundant drinking water for the residents. At an early stage of the development of Xidi village, dwellings were built between Qian Stream and Hou Stream.

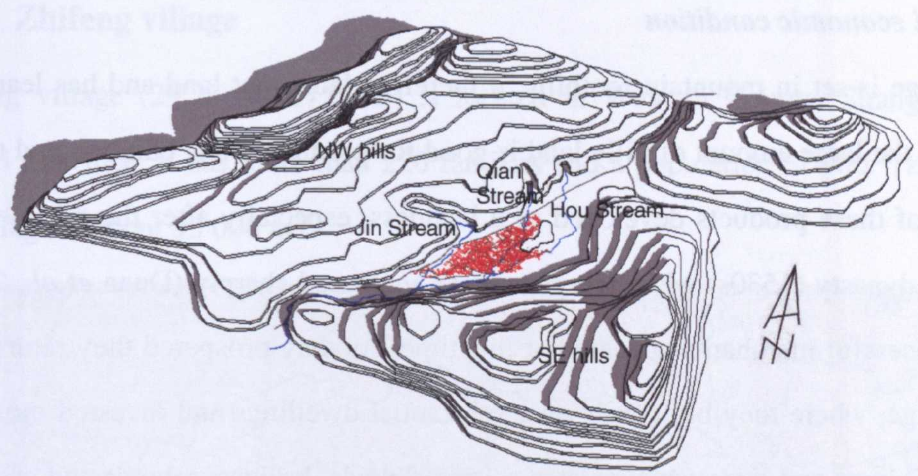


Figure 3. 3 Location of Xidi village within surrounding hills

There is a local folk saying to the effect that it would be highly auspicious for a boat to sail in Xidi. Whether by accident or design, the village appears to have evolved in a 'boat' shape – sharp at the village's two ends and wide in the middle (figure 3.4).

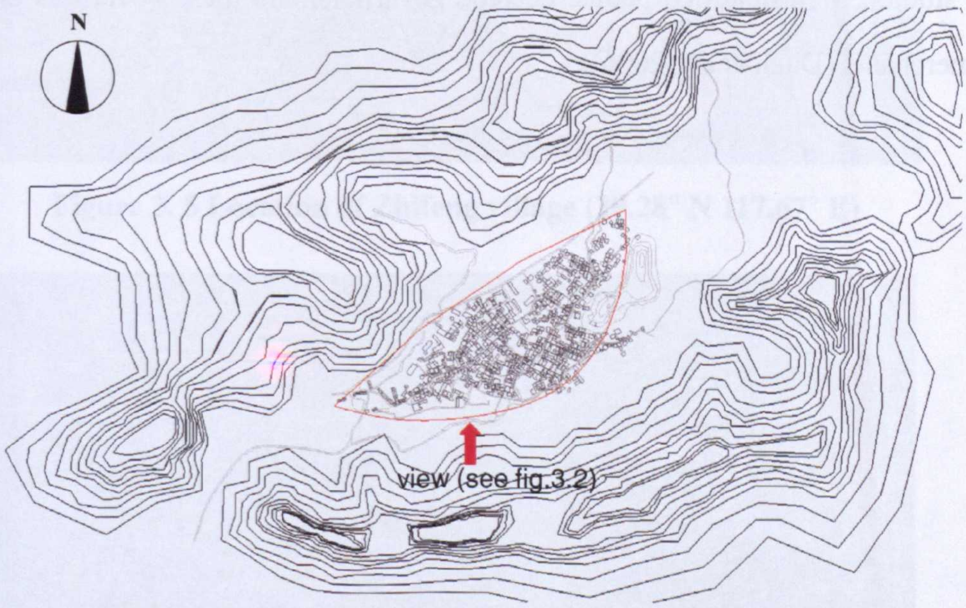


Figure 3. 4 'Boat' shape of Xidi village

Historical economic condition

Xidi village is set in mountain foothills; it therefore lacks flat land and has lean soil. However, the large amount of hilly land is good for producing tea, bamboo and timber. The sale of these products developed as a business, especially after the mid-point of the Ming dynasty (1530s) when the population increased sharply (Duan *et al.*, 2006). Many successful merchants appeared at this time. As they prospered they returned to their village, where they built their own substantial dwellings and invested money in public buildings and infrastructure such as paved roads, bridges, schools and ancestral halls. Xidi village began to flourish and village inhabitants started to move away from agricultural labour. About 60% of residents were from families engaged in business. Most of the land was rented to people from outside the village who did not have the surname Hu. Several small villages formed around Xidi village to provide services. During this period, a virtuous circle developed – wealthy merchants supported people who studied, well-qualified people became governors, and these governors protected the merchants (Duan *et al.*, 2006).

3.2.2 Zhifeng village

Zhifeng village (29.28°N 117.67°E) is located in Wuyuan County, Shangrao City, Jiangxi Province. It has more than 220 families and a population of 900. The area of the village is about 93 000 m^2.

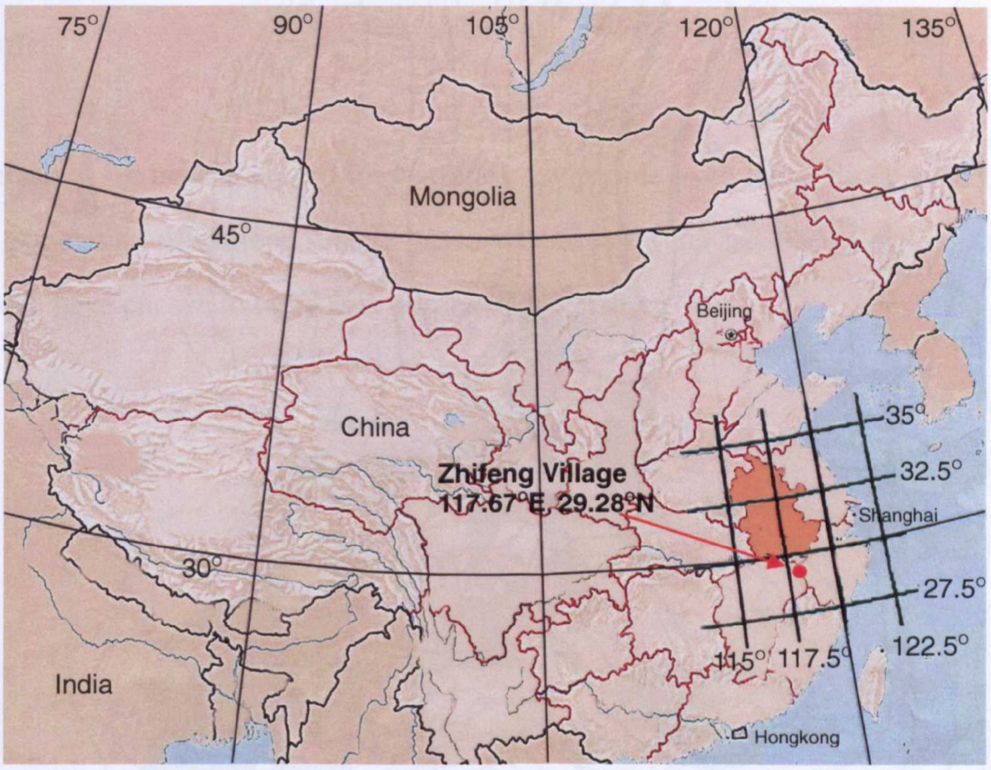


Figure 3. 5 Location of Zhifeng village (29.28° N 117.67° E)

Figure 3. 6 View of Zhifeng village from the south

Physical geography

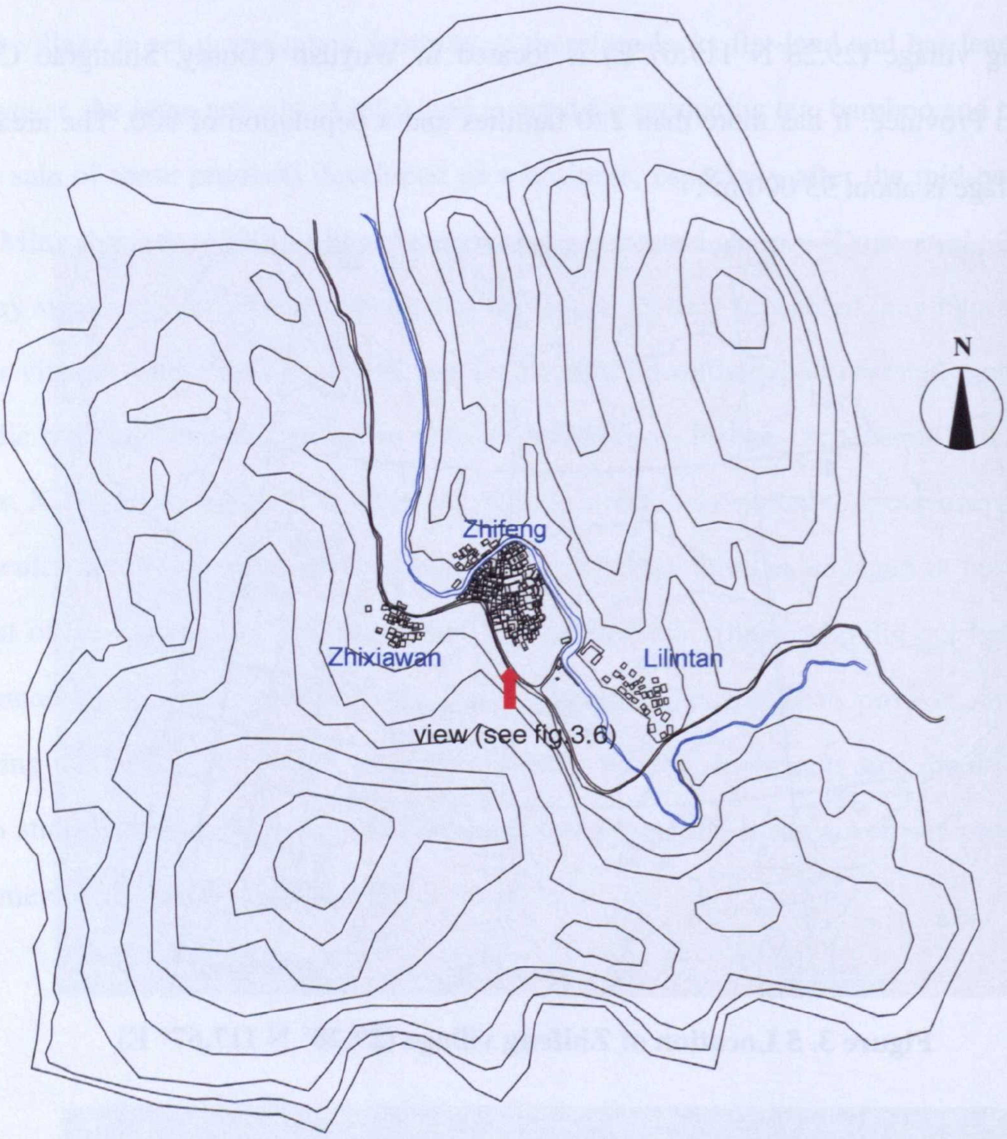


Figure 3. 7 Three parts of Zhifeng village - Zhixiawan, Zhifeng and Lilintan

Zhifeng village is enclosed by mountains and a stream, and is divided into three parts – Zhixiawan, Zhifeng and Lilintan (figure 3.7). The elevation of the village is about 110 m and the relative heights of its surrounding hills range from 40 m to 130 m above this. The earliest inhabitants settled in the Zhixiawan area were because of the presence of two springs with good quality water that continued to flow throughout the year. Zhixiawan grew, and became overcrowded. When the population exceeded 36 families (around the 11st century) and no more could be accommodated, some inhabitants established houses in the Zhifeng district, which had previously been under cultivation. According to historical records, Pan Chugong, who was an authority in Fengshui, declared that Zhifeng area of the village was exceptionally favorable according to geomantic criteria (Gong, 1999). This encouraged more people to move there. The traditional dwellings of Zhifeng village are mainly located in the Zhifeng district.

Lilintan is far from water, so for centuries few people lived there. Since the 1990s, as the population of Zhifeng village increased and tap water has been supplied, so more people have chosen to build new houses in this district.

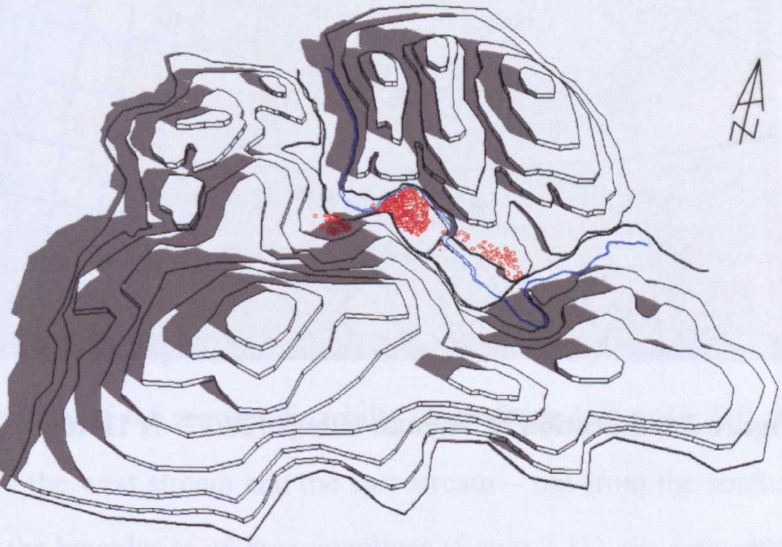


Figure 3. 8 Location of Zhifeng village within surrounding hills

Historical economic condition

There are not many tillable fields near the village apart from a few terraced fields planted with vegetables in the nearby foothills. Most of the cultivated fields are located in the flat lands behind the surrounding hills. Zhifeng is the principal grain producing area of Wuyuan. Historically, its economy relied mainly on agriculture with commerce being subsidiary. More than 60% of residents were from families that worked in the fields. Fields are generally about 1000 m from the residents' houses.

3.2.3 Yuyuan village

Yuyuan village (28.77°N 119.66°E) is in Wuyi County, Jinhua City, Zhejiang Province. It has more than 600 families and a population of 2000. The village was an area of about 207 000 m^2.

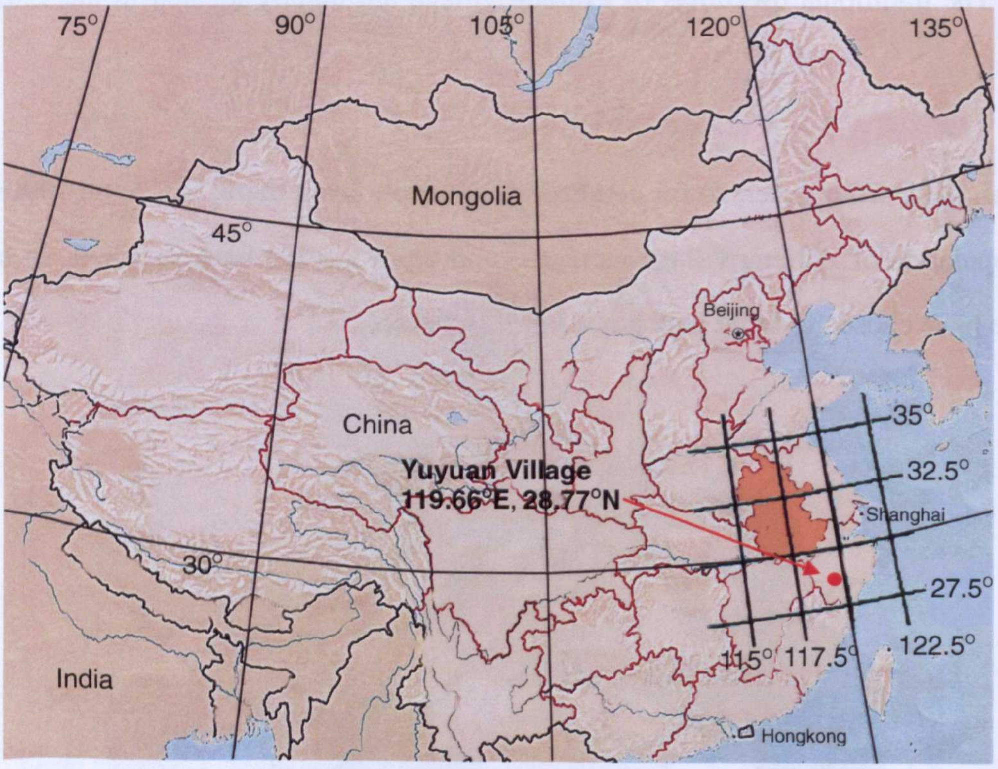


Figure 3. 9 Location of Yuyuan village (28.77° N 119.66° E)

Figure 3. 10 View of Yuyuan village from the north (Wuyi – China, 2005)

Physical geography

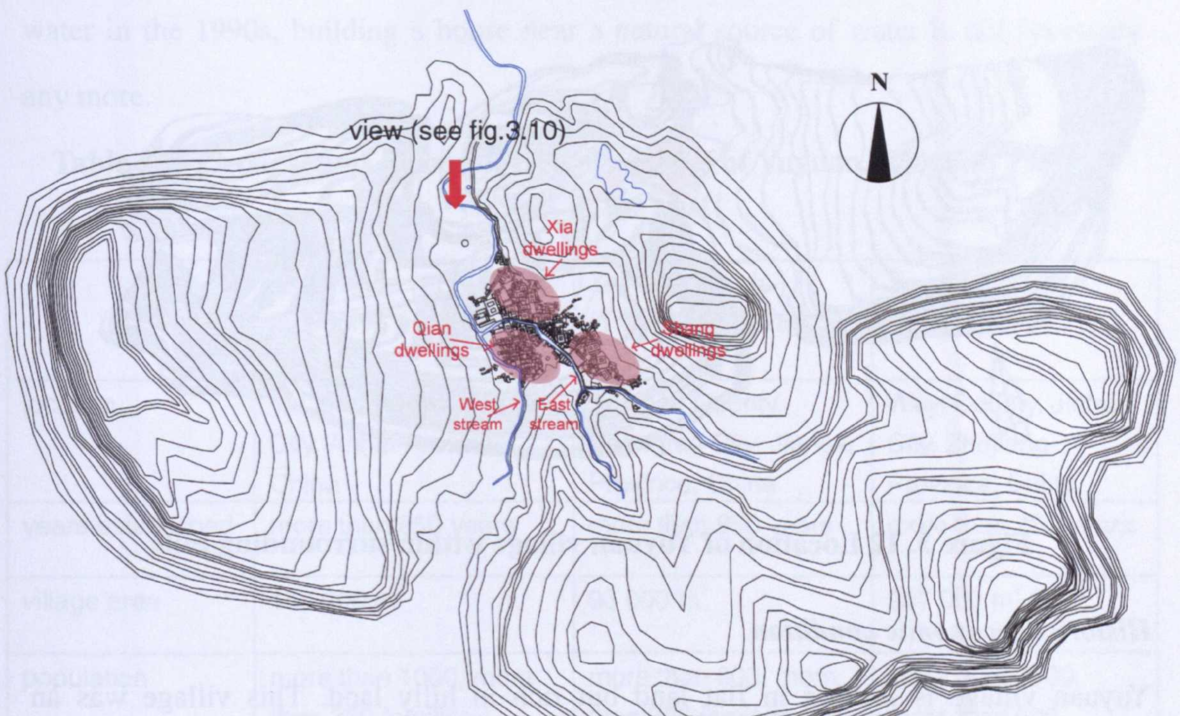


Figure 3. 11 Site plan of Yuyuan village

The elevation of the village is about 170 m within a valley which runs from north to south. The heights of the surrounding hills range from 180 m to 340 m above this. Two streams – the west stream and the east stream – run from the south to north and merge within the boundaries of Yuyuan village (figure 3.11). the west stream is 8-10m wide, the east stream 10-15m wide. The village is divided into two parts by the streams. The area of the village north of the east stream is about 600 m x 170 m while the other part between West stream and East stream is 230 m x 200 m. The village has discrete areas known as the Shang dwellings, Xia dwellings and Qian dwellings. Residents of the Shang dwellings were the richest while the poorest residents lived in Qian dwellings.

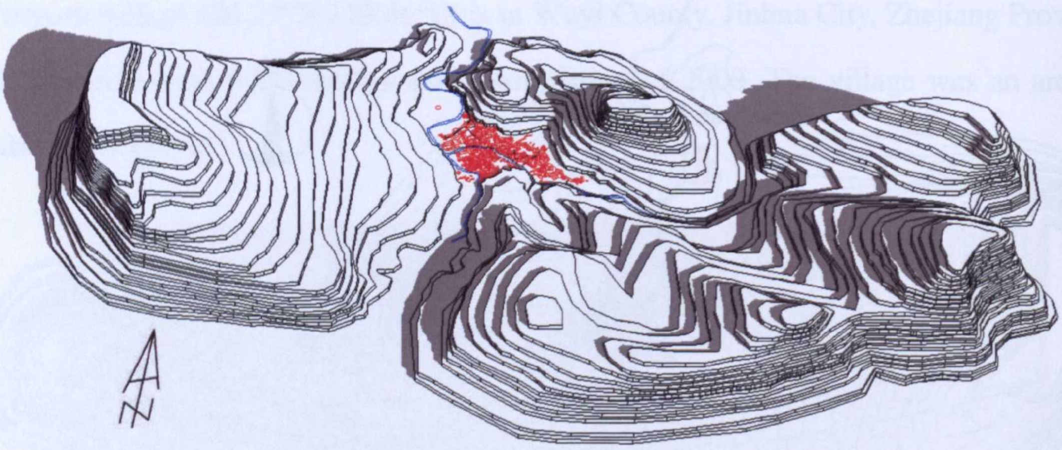


Figure 3. 12 Location of Yuyuan village within surrounding hills

Historical economic condition

Yuyuan village is lacking in flat land but rich in hilly land. This village was an important transport junction, through which many people passed when travelling from Wuyi city to Xuanping city. For this reason that there were more shops and restaurants in this village rather than in Xidi or Zhifeng. Increasing numbers of village inhabitants started to run businesses and Yuyuan village began to flourish. At this time, about 80% of residents belonged to families which derived their income from agricultural related business or catering. These families also owned a large amount of land outside the village, families owning land outside the village would obtain an income from renting this out (Chen, 2007).

3.2.4 Summary

The physical and economic characteristics of the three villages studied are summarized in Table 3.1. The three villages are in the eastern part of China with similar latitude and longitude. They are all in hilly areas. Taking the villages as reference points, the elevations of the hills surrounding Xidi village, Zhifeng village and Yuyuan village are 120 m – 200 m, 40 m – 130 m, and 180 m – 340 m respectively. Each of the three villages developed around at least one stream because of the need for easy access to water for drinking and washing. With the advent of tap water in the 1990s, building a house near a natural source of water is not necessary any more.

Table 3. 1 Physical and economic characteristics of Yuyuan, Xidi and Zhifeng villages in the past

	Xidi Village (117.992E, 29.906N)	Zhifeng Village (117.67E, 29.276N)	Yuyuan Village (119.662E, 28.77N)
location	Yi County, Huangshan City, Anhui Province, China	Wuyuan County, Shangrao City, Jiangxi Province, China	Wuyi County, Jinhua City, Zhejiang Province, China
years established	more than 950 years	more than 850 years	more than 750 years
village area	150 000 m^2	93 000 m^2	207 000 m^2
population	more than 1000, more than 350 families	more than 900, more than 220 families	more than 2000, more than 600 families
elevation	230 m	110 m	170 m
elevation of surrounding hills (with respect to sea level)	350m - 430m	150m - 240m	350m - 510m
elevation of surrounding hills (above village)	120 m – 200 m	40 m – 130 m	180 m – 340 m
historical economic condition	rich, about 60% of residents from families engaged in non-agricultural business	poor, more than 60% of residents from families doing agricultural work. Fields generally about 1000 m from houses.	wealthy, about 80% of residents from families engaged in non-agricultural business
people's activities	Majority of men engaged in business outside the village and come back home a few times a year. Skywells of houses mainly used by women, children and the old.	Most residents do agricultural work. Skywells seldom used by people in the daytime and mainly used for storage in the nighttime.	Residents engaged in trade and run restaurants and shops in village. Skywells of housed used quite often.

3.3 Dwellings in three villages studied

Most of the houses in the three villages were built very close to each other, forming a very compact arrangement (figure 3.13 to 3.15). Many dwellings are semi-detached, or are arranged in short terraces. Most dwellings are separated by 1-2 m wide alley ways (figure 3.16). The main streets for transportation within the villages are only 3-6m wide.

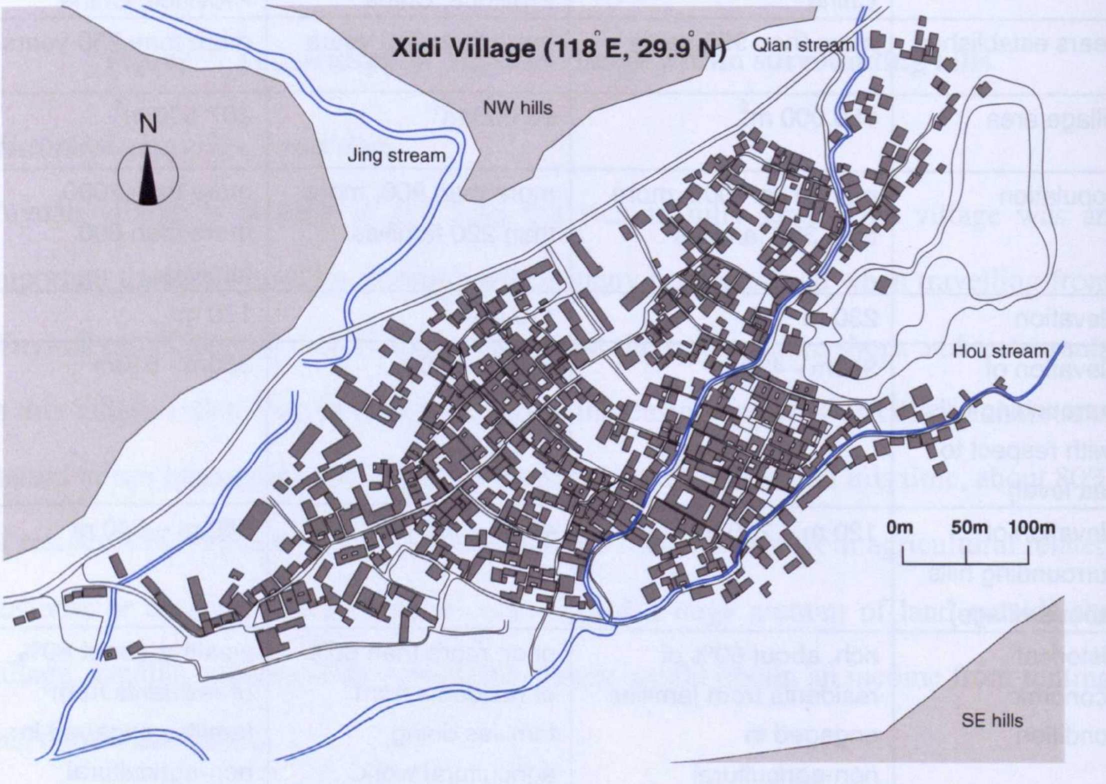


Figure 3. 13 Nolli plan of Xidi village

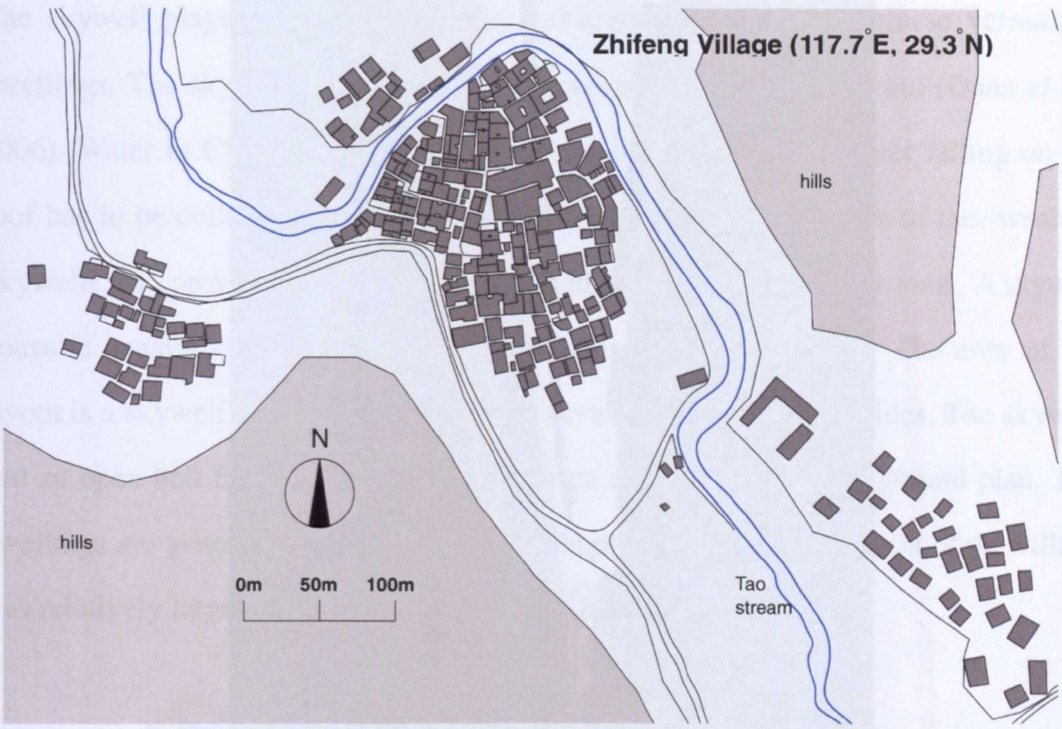


Figure 3. 14 Nolli plan of Zhifeng village

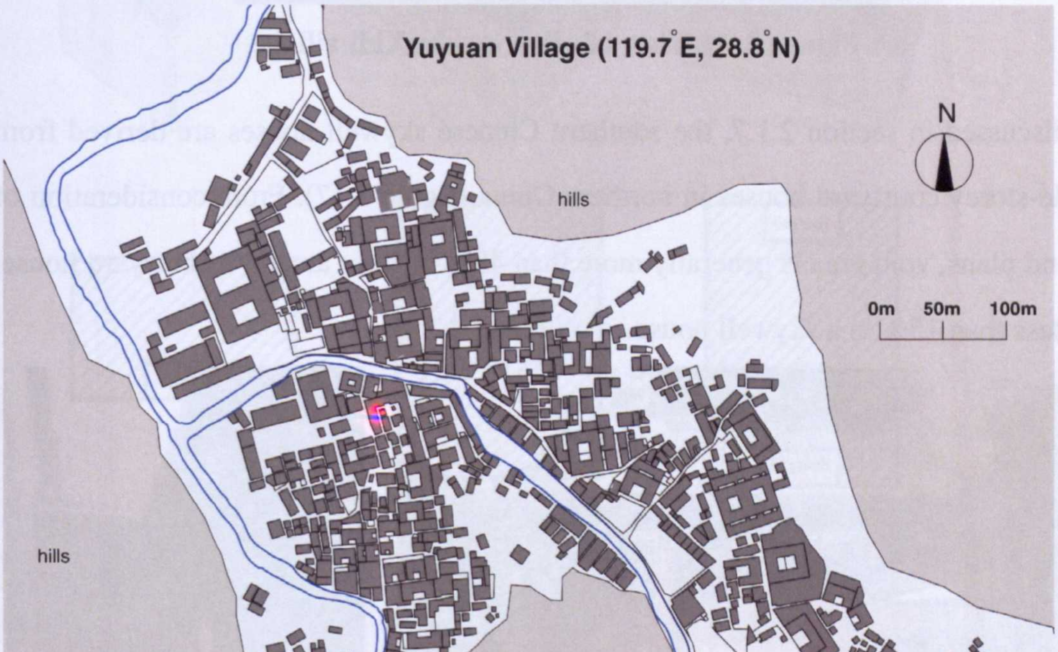


Figure 3. 15 Nolli plan of Yuyuan village

Figure 3. 16 View of alley way in Xidi village

As discussed in section 2.1.7, the southern Chinese skywell houses are derived from single-storey courtyard houses in northern China (figure 3.17). From consideration of ground plans, void area is generally more than 40% of floor area in a courtyard house, and less than 15% in a skywell house.

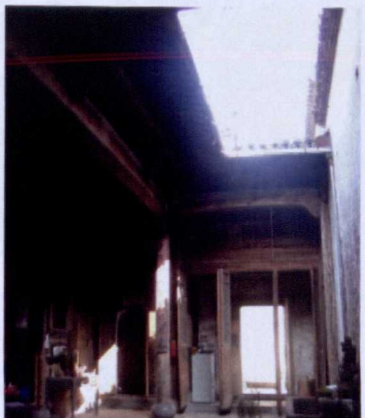


Figure 3. 17 Dwellings in northern China (left) showing large courtyard (http://lpdibiao.com/features/2012/249?page=2) and dwellings in southern China (right) showing small skywell

The skywell plays important symbolic and ergonomic roles in Chinese vernacular dwellings. The skywell is designed to collect water and catch the wind (Duan *et al.*, 2006). Water in Chinese culture represents wealth, therefore rainwater falling on the roof has to be collected and diverted into the house to avoid the loss of the 'wealth'. Skywells also provide daylighting and ventilation for their adjoining rooms. A skywell house is usually symmetrical and rectangular in plan (figure 3.18). The core of the layout is a skywell, with rooms around the skywell on three or four sides. The skywell and an open hall facing into the skywell lie on the long axis of the ground plan. The dwellings are generally two or three storeys high because the population of the village was relatively large in relation to its available land.

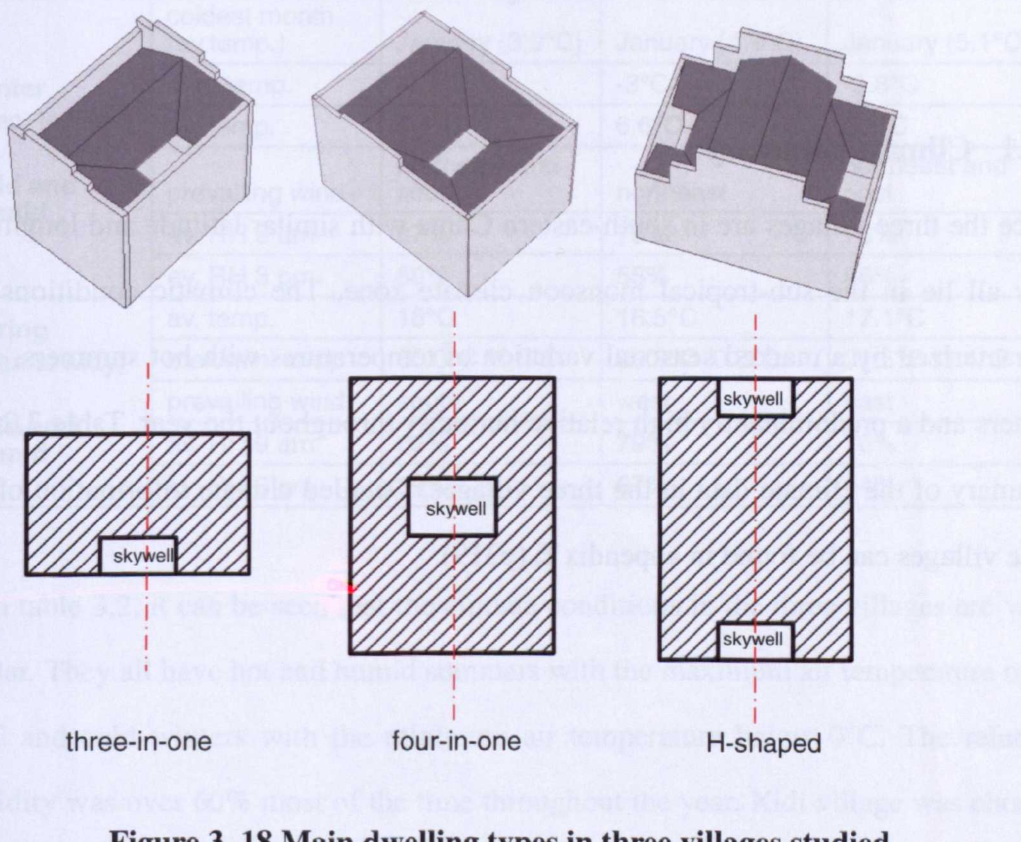


Figure 3. 18 Main dwelling types in three villages studied

Three main types of skywell dwelling can be found in these villages: the three-in-one skywell house, the four-in-one skywell house and the H-shaped skywell house (figure 3.18). The three-in-one type can be considered as a prototype while in the four-in-one skywell house, two three-in-one houses are joined together face-to-face, with a common skywell. In the H-shaped skywell house, two three-in-one houses are joined together back to back. They have individual skywells on opposite sides of the two-house block. Three–in–one skywell houses are mostly found in Xidi village and Yuyuan village while H-shaped skywell houses are mainly in Zhifeng village.

3.4 Site microclimatic study

The site microclimatic analysis seeks to identify the relationship between the village form and local environmental factors. A summary of climate data for Xidi, Zhifeng and Yuyuan villages will be presented first, and then the response to the hot summer and cold winter of houses in the three villages will be discussed.

3.4.1 Climate summary

Since the three villages are in south-eastern China with similar latitude and longitude, they all lie in the sub-tropical monsoon climate zone. The climatic conditions are characterized by a marked seasonal variation of temperatures with hot summers, cold winters and a predominantly high relative humidity throughout the year. Table 3.2 is a summary of the climate data in the three villages. Detailed climate information of the three villages can be found in appendix E (p319).

Table 3. 2 Summary of the climate data in Xidi, Zhifeng and Yuyuan village

season	climate data	Xidi village	Zhifeng village	Yuyuan village
summer (Jun. to Aug.) **hot and humid**	hottest month (av.temp.)	July (29.6°C)	July (29.0°C)	July (28.5°C)
	max. temp.	35.8°C	36.6°C	36.4°C
	av. temp.	28°C	27.7°C	27.2°C
	prevailing wind	northwest and south	north and northeast	northeast and southwest
	av. RH 9 am	82%	73%	76%
	av. RH 3 pm	62%	63%	65%
autumn (Sep. to Nov.) **warm and humid**	av. temp.	18.2°C	18.9°C	18.7°C
	max/min. temp.	35.1°C / 6°C	34.6°C / 5.9°C	34.3°C / 4.1°C
	prevailing wind	southeast and northwest	south and east	southeast
	av. RH 9 am	86%	72%	75%
	av. RH 3 pm	52%	56%	60%
winter (Dec. to Feb.) **cold and humid**	coldest month (av.temp.)	January (3.9°C)	January (4.9°C)	January (5.1°C)
	min. temp.	-0.7°C	-3°C	-0.8°C
	av. temp.	5.1°C	6.6°C	6.5°C
	prevailing wind	northeast and south	northeast	northeast and east
	av. RH 9 am	87%	73%	75%
	av. RH 3 pm	58%	55%	66%
spring (Mar. to May) **mild and humid**	av. temp.	16°C	16.5°C	17.1°C
	max/min. temp.	30.0°C /1.0°C	29.8°C /0.8°C	31.5°C /3.4°C
	prevailing wind	south	west	east
	av. RH 9 am	82%	79%	76%
	av. RH 3 pm	59%	67%	64%

From table 3.2, it can be seen that the climate conditions in the three villages are very similar. They all have hot and humid summers with the maximum air temperature over 35°C and cold winters with the minimum air temperature below 0°C. The relative humidity was over 60% most of the time throughout the year. Xidi village was chosen to exemplify the climatic features of the three villages and was studied in detail. The psychrometric chart on fig 3.19 shows the generalized comfort zones in which most people would feel thermally comfortable in summer and winter, combining air temperature and relative humidity. Whilst the effect of the building on indoor conditions is not considered, the zones are indicators of the extent to which buildings is required to modify the local microclimate to provide comfortable conditions for its occupants. The black points represent the hourly data of temperature and relative humidity in Xidi village while the areas within the closed red lines represent comfort zones in still air conditions.

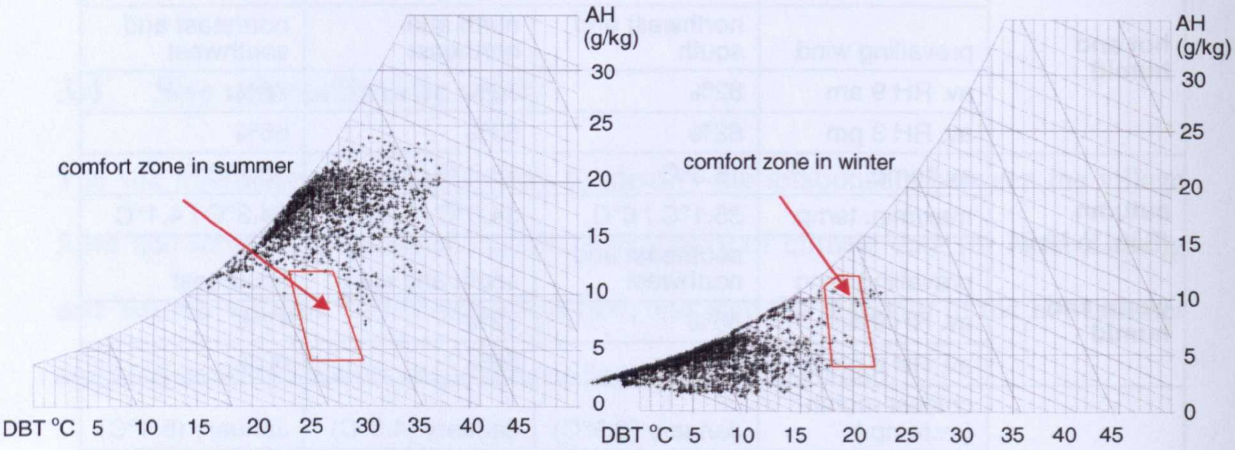


Figure 3. 19 Psychrometric charts showing summer and winter comfort boundaries in Xidi village

From the concentration of the bulk of the points in relation to the comfort zones it is evident that the inhabitants of Xidi village will need to have substantial heating during winter, and to prevent excessive heat gain and humidity in summer.

It can be seen in figure 3.20 that with the provision of air movement at 1ms^{-1}, the area of the comfort zone for summer (enclosed by the blue border) in the region where the villages are located is more than three times that of the summer comfort zone in the same geographical region when no natural ventilation is applied (the comfort zone in the absence of natural ventilation is the area enclosed by the red border). Thus, the duration of the period in which residents will feel comfortable is extended considerably. In figure 3.21, solar radiation can be seen to double the area of the comfort zone (compare the areas enclosed by the blue and red borders). However, most of the temperature/humidity data points obtained from the nearest weather station over the winter period still fall outside the comfort zone. It can be seen that residents need to heat their house in winter even when taking full advantage of solar radiation. (Comfort zones in the presence and absence of natural ventilation or solar radiation are as defined in Ecotect.)

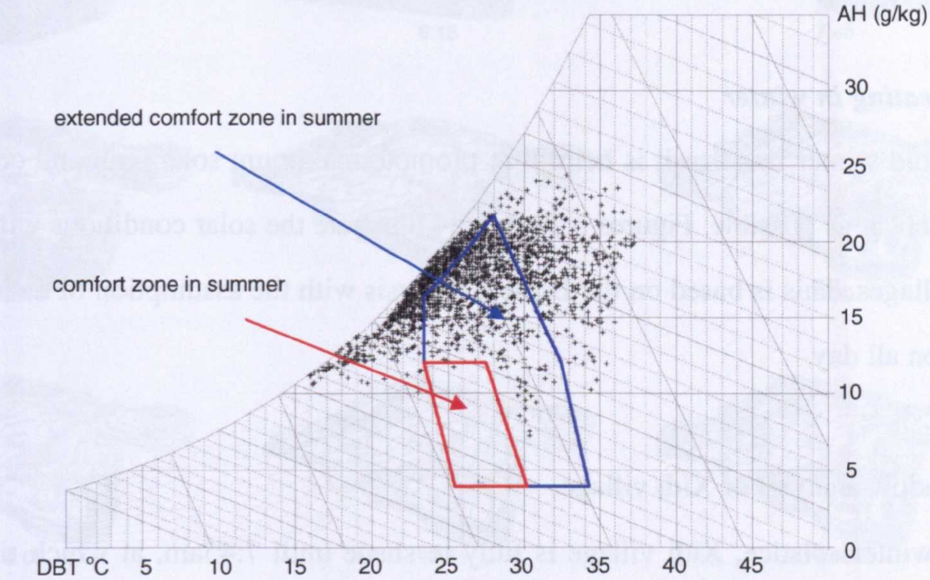


Figure 3. 20 Psychrometric chart displaying data for summer period (1/6 – 31/8) from Tunxi weather station, showing potential extension of summer comfort zone by use of natural ventilation

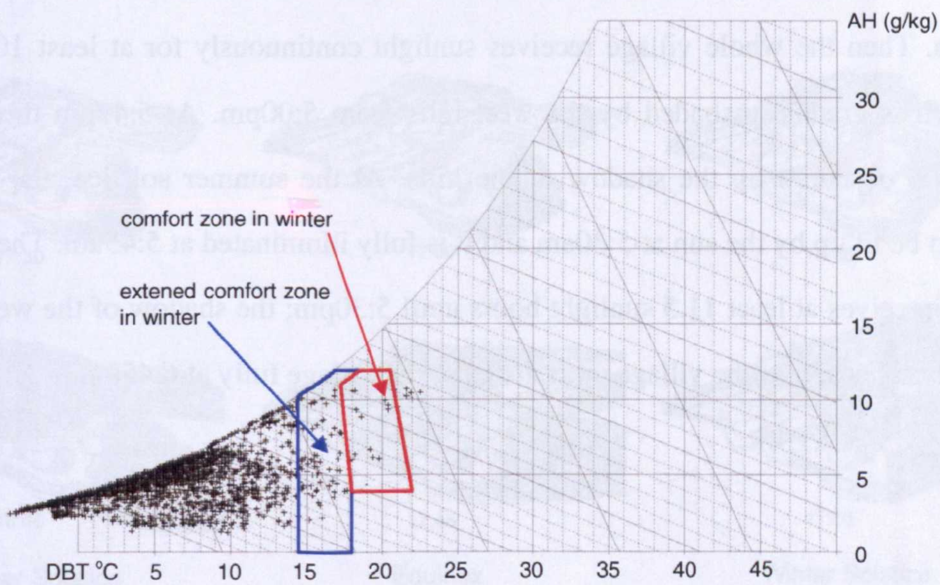


Figure 3. 21 Psychrometric chart displaying data for winter period (1/12 – 28/2) from Tunxi weather station, showing potential extension of winter comfort zone by use of solar radiaiton

3.4.2 Environmental responses of the three villages

The response to the hot summer and cold winter of buildings in the three villages are discussed below.

Solar heating in winter

In the cold winter months, it is helpful to promote maximum solar gain and conserve as much heat as possible. Figures 3.22 to 3.24 illustrate the solar conditions within the three villages. This is based on the Ecotect analysis with the assumption of a clear sky condition all day.

1) Shadow analysis of Xidi village

At the winter solstice, Xidi village is fully in shade until 7:45am, at which time the sun begins to illuminate the village. The whole village is exposed to the sun from 8:30am until 4:00pm. The hills to the west of the village project long shadow from 4:00pm onward, covering the whole village at 5:00pm. At the equinox, the village starts to receive sunlight from 6:15am and it is completely illuminated by the sun at 6:45am. Then the whole village receives sunlight continuously for at least 10 hours and then is gradually shaded by the west hills from 5:00pm. At 5:45pm the whole village is obscured by the shadow of the hills. At the summer solstice, the village starts to be lit up by the sun at 5:30am and it is fully illuminated at 5:45am. The whole village receives at least 11.5 sunlight hours until 5:30pm; the shadow of the west hills then advances across the village until it shades the village fully at 6:45pm.

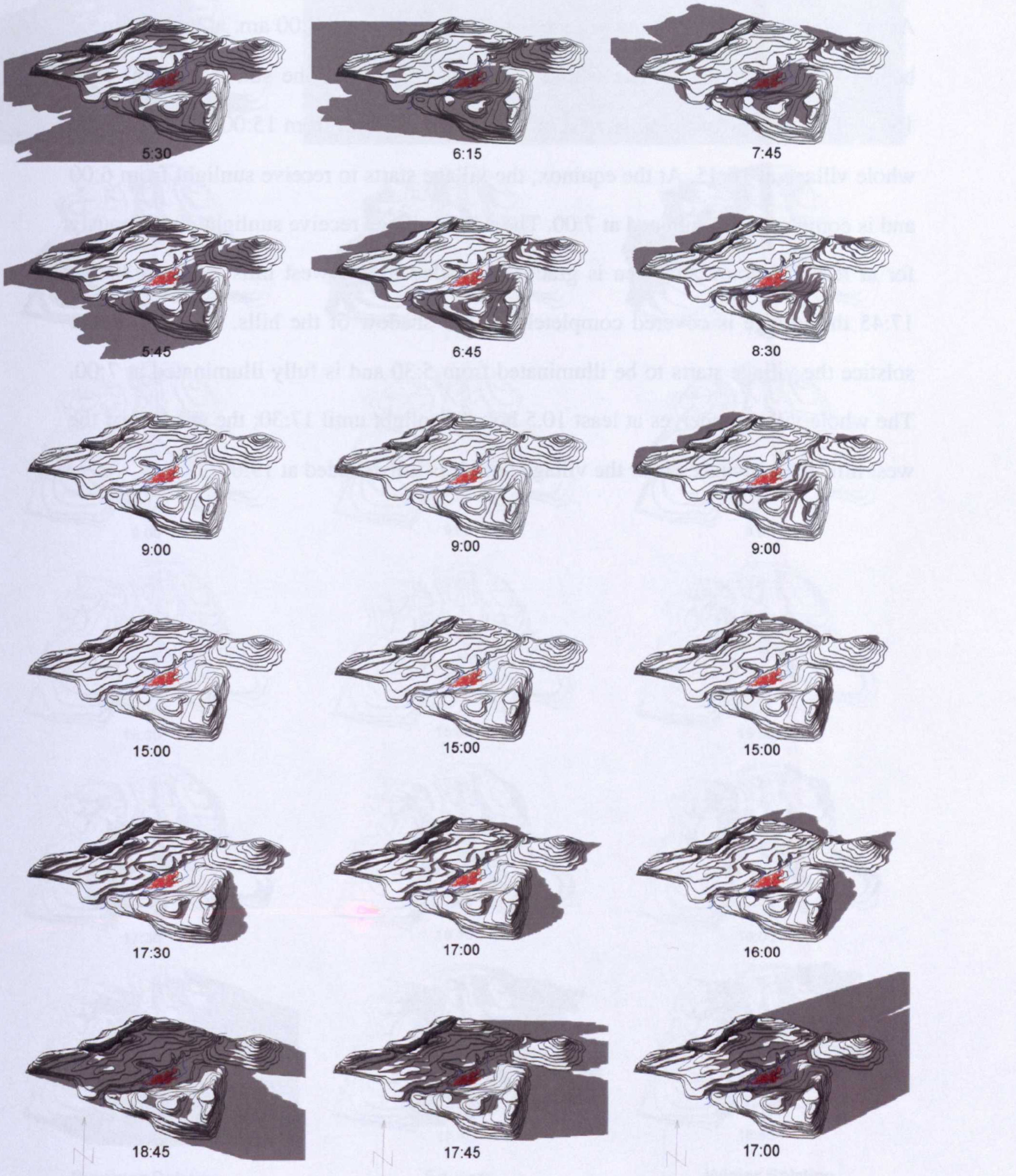


Figure 3. 22 Shadow analysis of Xidi site

2) Shadow analysis of Zhifeng village

At the winter solstice, Zhifeng village is fully in shade until 7:00 am, at which time it begins to be illuminated. The whole village is exposed to the sun from 9:00 until 15:00. The shadow of the hills west of the village enlarges from 15:00 and covers the whole village at 16:45. At the equinox, the village starts to receive sunlight from 6:00 and is completely illuminated at 7:00. The whole village receive sunlight continuously for at least 10 hours and then is gradually shaded by the west hills from 16:30. At 17:45 the village is covered completely by the shadow of the hills. At the summer solstice the village starts to be illuminated from 5:30 and is fully illuminated at 7:00. The whole village receives at least 10.5 hours' sunlight until 17:30; the shadow of the west hills then advances over the village until it is fully shaded at 19:00.

Figure 3. 23 Shadow analysis of Zhifeng site

3) Shadow analysis of Yuyuan village

At the winter solstice, Yuyuan village is fully in shade until 7:30 in the morning, at which time it begins to be illuminated. The whole village is exposed to the sun from 8:15 until 15:30. The shadow of the hills west of the village enlarges from 15:30 and covers the whole village at 16:30. At the equinox, the village starts to receive sunlight from 6:30 and is completely illuminated at 7:30. The whole village receive sunlight continuously for at least 9 hours and then is gradually shaded by the west hills from 16:30. At 17:15 the village is covered completely by the shadow of the hills. At the summer solstice the village starts to be illuminated from 6:00 and is fully illuminated at 8:00. The whole village receives at least 9.5 hours' sunlight until 17:30; the shadow of the west hills then advances over the village until it is fully shaded at 18:30.

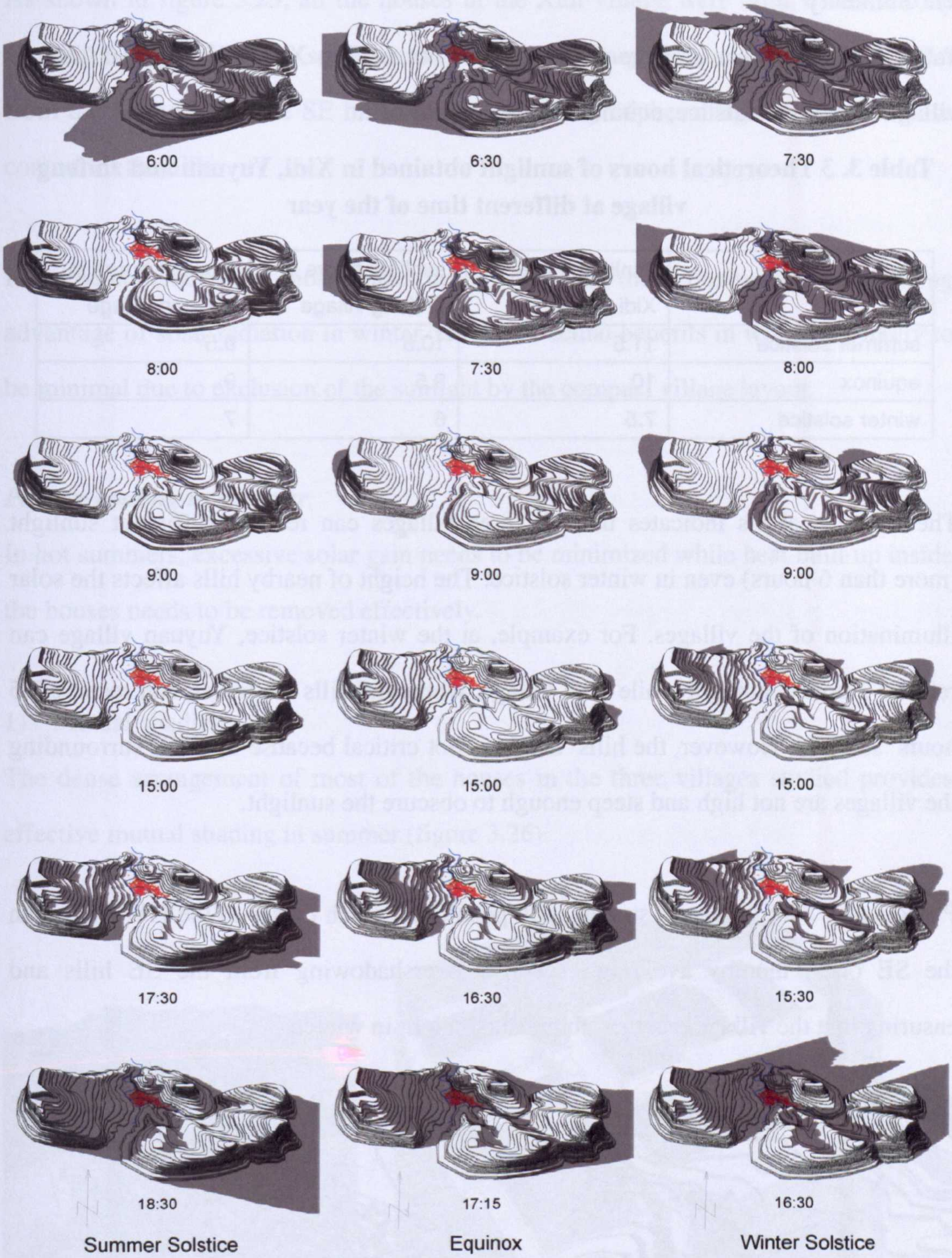


Figure 3. 24 Shadow analysis of Yuyuan site

1) Summary

Table 3.3 is a summary of the sunlight hours obtained in Xidi, Zhifeng and Yuyuan village at summer solstice, equinox and winter solstice.

Table 3. 3 Theoretical hours of sunlight obtained in Xidi, Yuyuan and zhifeng village at different time of the year

time	sunlight hours in Xidi village	sunlight hours in Zhifeng village	sunlight hours in Yuyuan village
summer solstice	11.5	10.5	9.5
equinox	10	9.5	9
winter solstice	7.5	6	7

The above analysis indicates that all three villages can receive sufficient sunlight (more than 6 hours) even in winter solstice. The height of nearby hills affects the solar illumination of the villages. For example, at the winter solstice, Yuyuan village can receive 7 hours' sunlight while Xidi village, where the hills are lower, can receive 7.5 hours' sunlight. However, the hills' height is not critical because the hills surrounding the villages are not high and steep enough to obscure the sunlight.

Particularly, Xidi village is strategically positioned much closer to the NW hills than the SE ones, thereby avoiding excessive overshadowing from the SE hills and ensuring that the village receives abundant sunlight in winter.

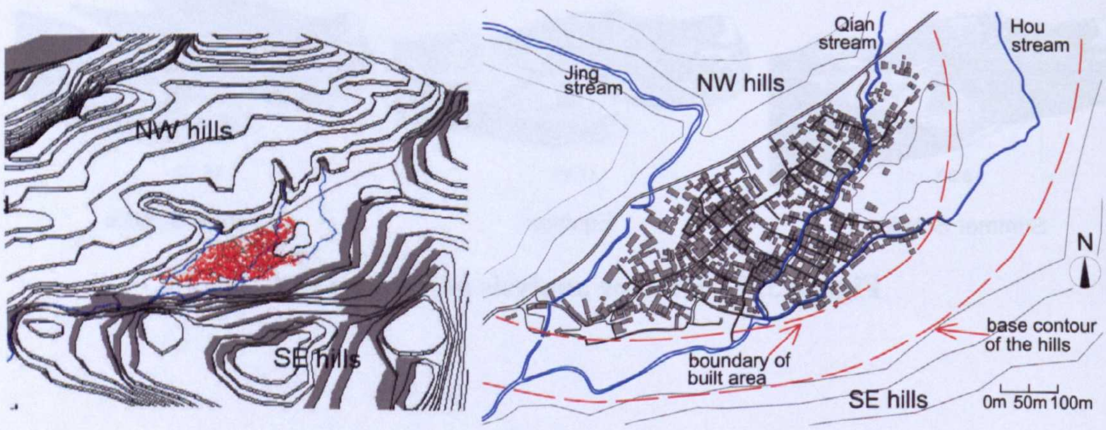


Figure 3. 25 Xidi village is located much closer to the NW hills than to the SE hills

As shown in figure 3.25, all the houses in the Xidi village were built within a zone abutting the NW hills. The southern and eastern boundary of the village is about 110m from the boundary of the SE hills; the site boundary of the village follows the base contour of the hills.

It can be concluded that most houses in the village are theoretically capable of taking advantage of solar radiation in winter. However, actual benefits in winter are likely to be minimal due to exclusion of the sunlight by the compact village layout.

Passive cooling in summer

In hot summers, excessive solar gain needs to be minimized while heat built up inside the houses needs to be removed effectively.

1) Mutual shading

The dense arrangement of most of the houses in the three villages studied provides effective mutual shading in summer (figure 3.26).

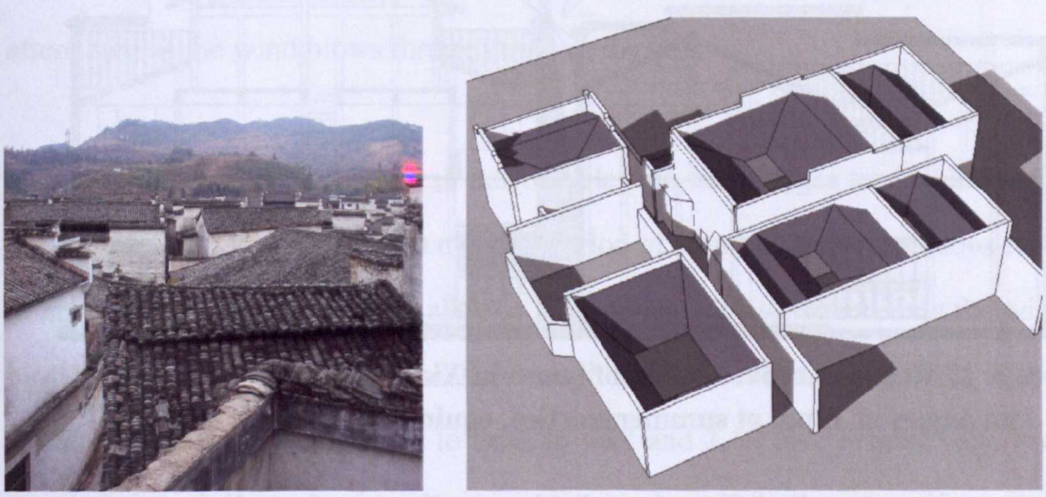


Figure 3. 26 Photograph and Ecotect modelling of a group of dwellings in Xidi village, showing compact housing arrangement

The compact grouping of houses rarely allows sunlight to reach the occupied level in the alleys even at noon (figure 3.27), as a result, this can effectively protect the house walls and pedestrians from the intense summer sun. In site monitoring, it was found that at 09:00am on 13th August 2009, the measured air temperature was 26.9°C and the relative humidity was 82.9% outside Dunren Hall. At this time of the day, the external surface temperature of the upper part of the external wall was about 33°C because this part of the wall was strongly illuminated by the sun. In the shaded middle part of the wall, the surface temperature was 3°C lower than that of the upper part, while at the lower part of the wall, the surface temperature was only 28°C. The data indicate the effectiveness of mutual shading for reducing excessive solar heat gain at the occupied level of the dwelling, making the alleys and ground level of the houses more bearable in high summer. In addition, the light colour of the external wall surfaces also enhances the reflection of light, reducing the heat absorbed by the dwellings, and further improving the comfort within the alleys between houses.

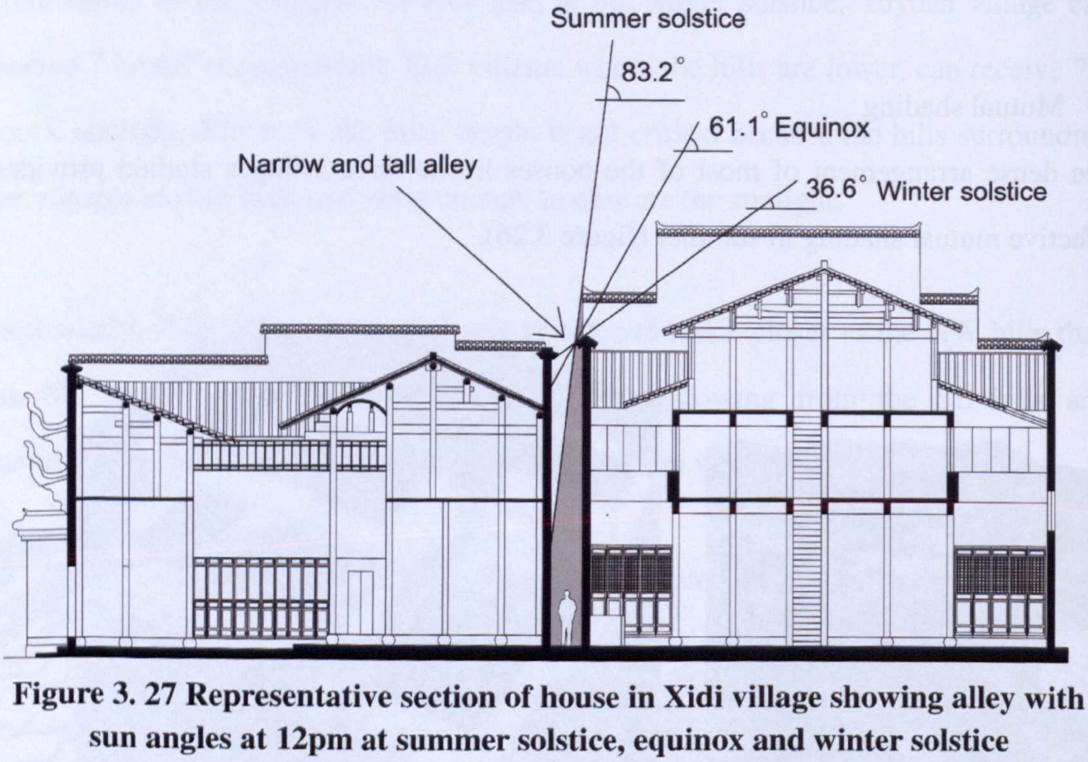


Figure 3. 27 Representative section of house in Xidi village showing alley with sun angles at 12pm at summer solstice, equinox and winter solstice

Furthermore, the narrow and deep skywells do not allow much sunlight to penetrate into the interior of the dwellings. This will be discussed in detail in section 6.3.

2) Natural ventilation

Prevailing wind directions in the three villages are shown in table 3.2. However, these data were not obtained from local sites but from weather stations nearest to each village. Wind movements in hilly areas are complex. Wind direction and speed change frequently due to the presence of hills, trees and other obstructions. Besides wind arising from outside the village, mountain and valley floor breezes within the village could be generated due to the summits of the surrounding hills receive more solar radiation than the lower and flatter area in which the village is located. This leads to the establishment of strong atmospheric convection currents. The wind environment within the village is also influenced by the size and location of the dwellings and the width of the alleys.

Wind speed can be assumed to be reduced by the shelter conferred by the hills, as described by Littlefair *et al.* (2000). Since the three villages are all surrounded by ranges of hills which act as natural wind barriers, the houses in the villages are shielded from cold winter winds. The hills also reduce the speed of the wind flowing through the village in summer. The high temperature of the wind is likely to be attenuated as the wind blows through trees in the hills.

By acting as wind funnels, the tall narrow alleys in the villages tend to increase wind speeds in the built zone. In a 10 minutes period of simultaneous continuous recording in an open space and adjoining alley in Xidi village, during which time the wind was blowing from the open space directly through the alley, mean wind speeds in the open space and the alley were found to be 0.86 ms^{-1} and 1.18 ms^{-1} respectively. It can be concluded that wind speed increases as the air enters the alley to maintain the same rate of air flow in the alley as in the open space.

In the summer daytime, residents prefer to keep the external doors of traditional houses open – both the doors of the main entrance and the doors to annexes. This allows the interior of the houses to be connected with the complex network of external alleys. With the presence of skywells, air movement induced by wind is facilitated and natural ventilation is made possible across the entire village. To illustrate the effect on inducing air movement by opening the external doors, a simple experiment was carried out in Dunren dwelling on site. With the house doors (main entrance and secondary entrance) open, the wind speed at the main entrance was found to be 0.68 ms^{-1}, while the wind speed under the skywell was 0.21 ms^{-1}; with the doors closed, the wind speed under the skywell was reduced to 0.02 ms^{-1}. This indicates the effectiveness of connecting all air paths in the village to enhance natural ventilation, which removes excessive heat and humidity in summer. In winter, residents keep the doors closed to minimize heat losses due to the cold wind.

3.5 Conclusion

The three villages studied are all located in hilly areas of south-eastern China, and experience hot summers and cold winters. Each of the three villages developed around a stream because of the need for easy access to water for drinking and washing. The site planning of these villages have been found to be well suited to their local environmental conditions.

In hot summers, excessive solar gain needs to be minimized while heat built up inside the houses needs to be removed effectively. Although entire villages were exposed to intense solar radiation, the solar radiation that can be admitted by the narrow skywell is limited, and the densely arranged dwellings shade each other and cause the wind to flow rapidly through narrow alleys between the houses. These features help reduce the overall heat gain and cool the houses. When the doors of dwellings are open, all air paths in the village are connected. Natural ventilation is therefore facilitated effectively to remove the excessive heat and humidity. In hilly areas, local wind directions change frequently due to the presence of wind barriers of different shapes and sizes, creating complex airflow patterns.

In the cold winter months, it is helpful to receive maximum solar gain and to conserve as much heat as possible. In relation to the villages, the elevations of the hills surrounding Xidi village, Zhifeng village and Yuyuan village are 120m - 200m, 40m - 130m and 180m - 340m, respectively. Through the simulation using Ecotect, it can be found that although the height of the nearby hills limits the solar ingress of the village, the hills shield the village from cold winter winds, and all three villages can receive more than six sunlight hours even on the coldest day in winter. Practically, in order to receive more solar radiation, the Xidi village is located much closer to the NW hills than to the SE hills to avoid excessive overshadowing and to receive at least 7.5 sunlight hours even at the winter solstice. Closure of the main doors in the houses in winter also minimizes heat loss by reducing exchange of air between the interior and exterior.

While these villages were not built according to a carefully designed master plan, based on accumulated experiences and active responses to the site context and the challenges from the natural elements, the vernacular builders created a village that were well suited to their settings and environmental conditions.

Nolli plans of the three villages studied were drawn for the first time. Three main types of skywell dwelling can be found in these villages: the three-in-one skywell house, the four-in-one skywell house and the H-shaped skywell house. Through generation and inspection of the Nolli plans of the village it became apparent that in the three climatically similar villages, the mean size of the skywells differs considerably from village to village – large skywells were found in Yuyuan village (void area is 12.8% of floor area in average), medium skywells in Xidi village (void area is 5.7% of floor area in average) and very small skywells in Zhifeng village (void area is 1.4% of floor area in average) (figures 3.13 to 3.15). This can be explained by consideration of information obtained from local residents in interviews.

House form is influenced not only by the climate but also by the wealth of the occupants, their activities and the availability of materials. Of the three villages, Yuyuan was the richest with about 80% of residents being in families engaged in business. Many people in Yuyuan made a living from trading and from owning restaurants and shops. They built large houses with many bedrooms to enable several generations to live together. These dwellings necessarily enclose a large central area, and the skywells of these houses can be regarded as courtyards.

In Xidi, about 60% of residents were members of households which obtained their income from business. Men engaged in business outside the village and came back home a few times a year. Skywells were mainly used by women, children and the old for domestic work and recreation. Since men of working age were rarely present, security of the house became a high priority in house design, so skywells are not as large as those in Yuyuan village.

Zhifeng's economy relied mainly on agriculture with more than 60% residents being from farming families. The fields were generally about 1000m away from the farm workers' houses. Most of the farm labourers worked in the fields in the daytime. Zhifeng's skywell were seldom occupied in the daytime and were mainly used for storage. Skywells were therefore quite small, and tools and stored items placed within them were protected from rain.

4 OBSERVATION OF EIGHT DWELLINGS

4.1 Introduction

In chapter 3, the environmental context of Chinese vernacular skywell dwellings has been investigated. In order to assess daylighting and thermal performance within the dwellings and to evaluate the relationship between building design and performance; air temperature, relative humidity, daylighting value, surface temperatures and wind velocity within and outside the house were obtained. A total of 8 houses – Yingfu dwelling, Dunren dwelling and Lufu dwelling in Xidi village; Panmaotai dwelling and Panxianxiong dwelling in Zhifeng village; and Yufengfa dwelling, Gaozuo dwelling and Shuting dwelling in Yuyuan village – were investigated in detail. These dwellings were chosen because they are representative of the traditional dwellings in their villages, and because permission to study them was successfully obtained from the house owners.

The basic information of the eight dwellings including building dimensions and photographs will be presented in this chapter. The locally distinctive features common to the individual dwellings in the three villages and the differences between dwellings in different villages will be identified; this is the answer to research question 3 'Are any features common to the individual dwellings in each village? What are the differences between dwellings in different villages?' Subsequently, the obtained daylighting and thermal data will be described and analyzed in detail in chapters 5 and 6 respectively.

4.2 Description of eight dwellings

Traditional dwellings in the three villages have the typical white projecting 'horse-head' walls (i.e. the walls have a stepped profile at the sides and the highest point is at the centre) (figure 4.1), grey tiles and very few openings on the exterior walls. The tall horse-head wall provided security and also restricted the spread of fire from adjacent houses and provided acoustic privacy.

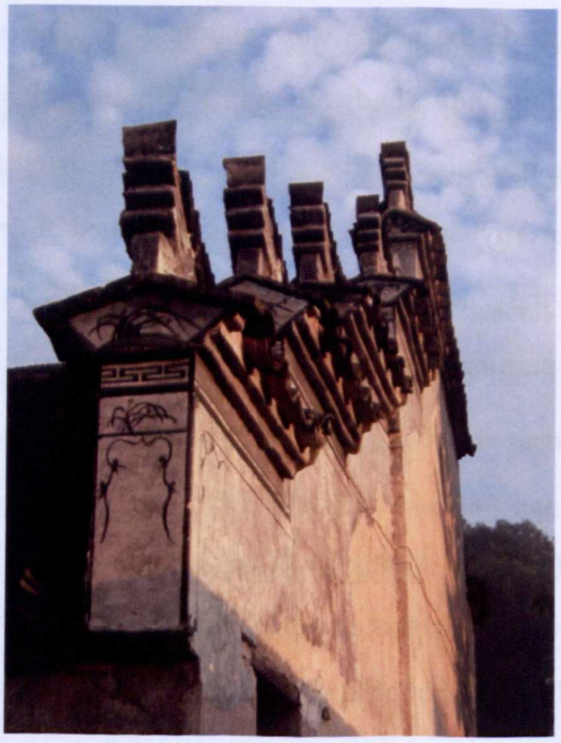


Figure 4. 1 View of horse-head wall (Zhai, 2007)

The size of skywells in the eight dwellings differs considerably. In the three villages studied – Yuyuan village, Xidi village and Zhifeng village – the mean proportions of floor area occupied by void area in the studied dwellings were 12.8%, 5.7% and 1.4% respectively.

Traditionally, residents of these dwellings would spend most of the daylight hours in the halls and skywells while at night they would stay in the bedrooms on the ground floor. There are bedrooms and a hall on the first floor of these buildings as well. The first floor hall was termed the ancestral hall, and was used for the performance of sacrifices to the residents' ancestors and other rituals.

Today only the ground floor of these dwellings is used for living while the upper floors are disused or else used for storage. This is due to changes in the composition of Chinese families. In the past, a Chinese family would consist of a sizeable group of people living together – grandparents, parents, several children and sometimes servants; today, there is only one child per family and he or she is likely to work or study far from home upon reaching adulthood. Therefore, the rooms on the ground floor are enough for a modern family. Older family members tend to prefer to live on the ground floor to avoid having to climb the stairs.

Kitchens and toilets were not constructed within skywell houses, but as outbuildings. Outbuildings were also created as additional storage spaces for some houses. These annexe structures were built to a height of one floor level and in a variety of shapes and sizes according to the space available around the skywell house (figure 4.2). Skywell houses were timber framed, and it is probable that kitchens were constructed as outbuildings in order to minimise risk from fire. Toilets were constructed outside the core of the house for hygiene and to exclude bad odours from the living space. In the architectural drawings in this thesis, the annexes are not shown.

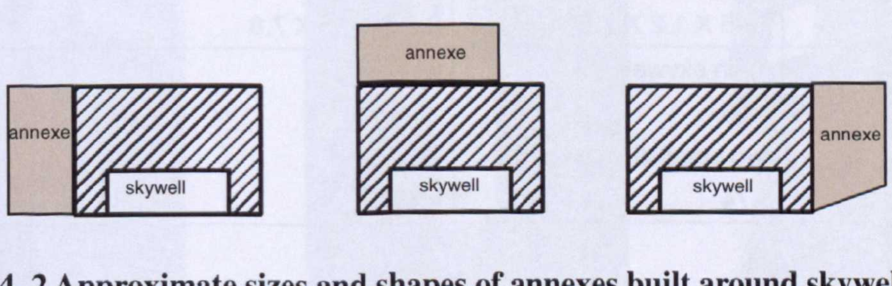


Figure 4. 2 Approximate sizes and shapes of annexes built around skywell houses

4.2.1 Xidi village dwellings

Of all the skywell houses in Xidi village, about 80% were three-in-one skywell house, 11% were four-in-one skywell house and 9% were H-Shaped skywell house. One of each type was chosen for further investigation – Yingfu dwelling (four-in-one), Lufu dwelling (H-shaped) and Dunren dwelling (three-in-one). Locations of these dwellings in Xidi village are shown in figure 4.3.

The basic information of three monitored dwellings in Xidi village is summarized in table 4.1. The groundfloor plan, section and photos of each selected house –Dunren dwelling (floor area 174m^2), Lufu dwelling (floor area 147m^2) and Yingfu dwelling (floor area 185m^2) – are shown in the following figures. More drawings in detail are supplied in the appendix C.

Table 4. 1 Summary of three studied dwellings in Xidi village

	Dunren dwelling	Lufu dwelling	Yingfu dwelling
building type	three-in-one	H-shaped	four-in-one
year of built	1722	1684	1664
floor area (m^2)	174	147	185
floors	two-storey	three-storey	two-storey
no of skywells	three	two	one
size of skywell L X W X H (m)	main skywell: 4.3 X 2.15 X 5.26 two small skywells: 1.45 X 1.2 X 7.6	west side: 2.3 X 1.3 X 7.5 east side: 3.3 X 1.35 X 7.8	4.2 X 1.8 X 6.8
area of skywell (m^2)	main skywell: 9.25 two small skywells: 1.74	west side: 2.99 east side: 4.46	7.56

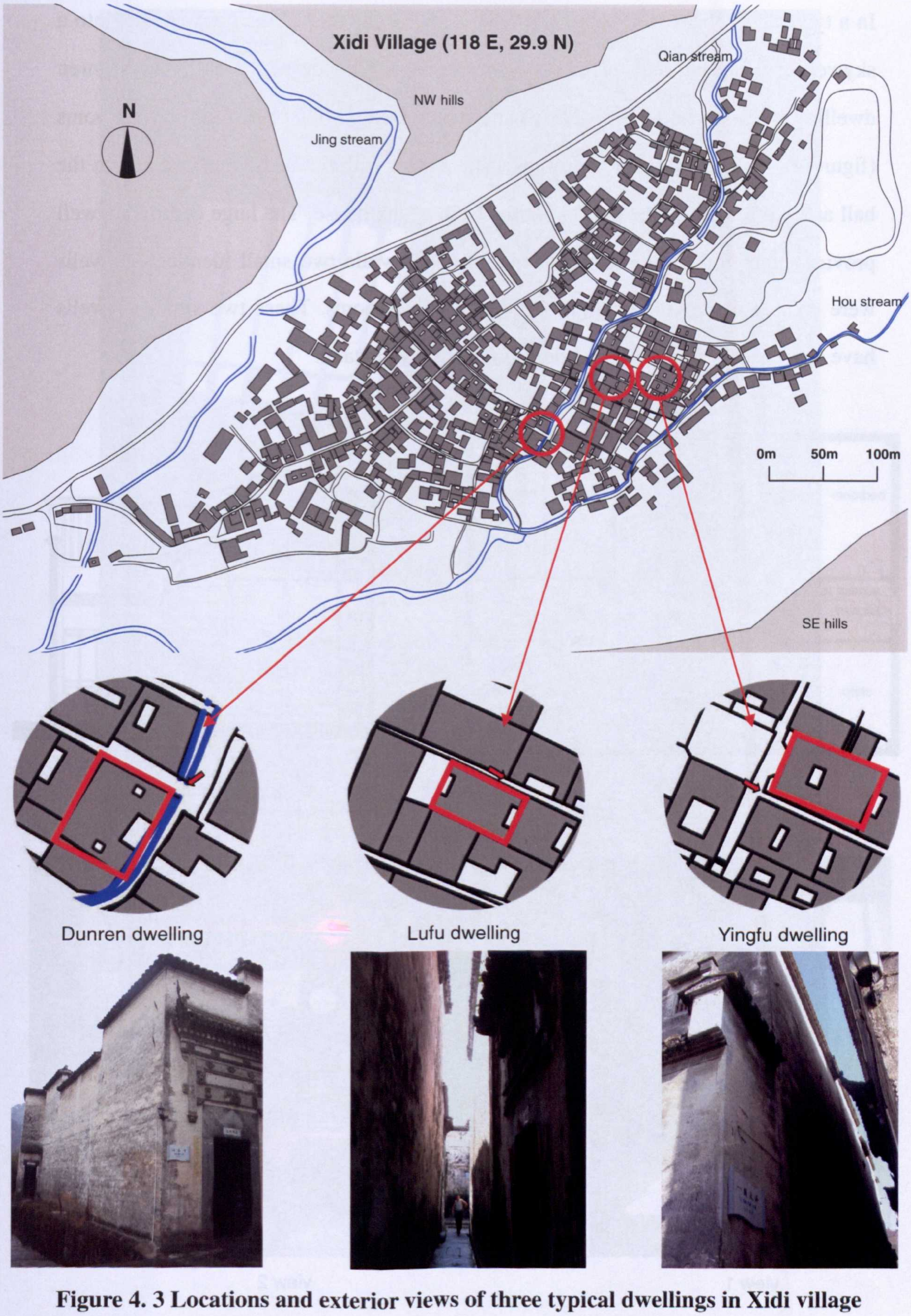


Figure 4. 3 Locations and exterior views of three typical dwellings in Xidi village

In a typical skywell house in Xidi village, a hall at the rear of the house opens into a skywell at the front, and there is a bedroom on either side of the hall. The Dunren dwelling is constructed on this basic pattern with the addition of two further bedrooms (figure 4.4). The additional bedrooms share a wall with the bedrooms that adjoin the hall and are remote to the hall along the back of the house. The large central skywell provides light for the bedrooms next to the hall while two small identical skywells were created to provide daylight for the two side rooms. These two small skywells have been glazed by modern residents to exclude rainwater.

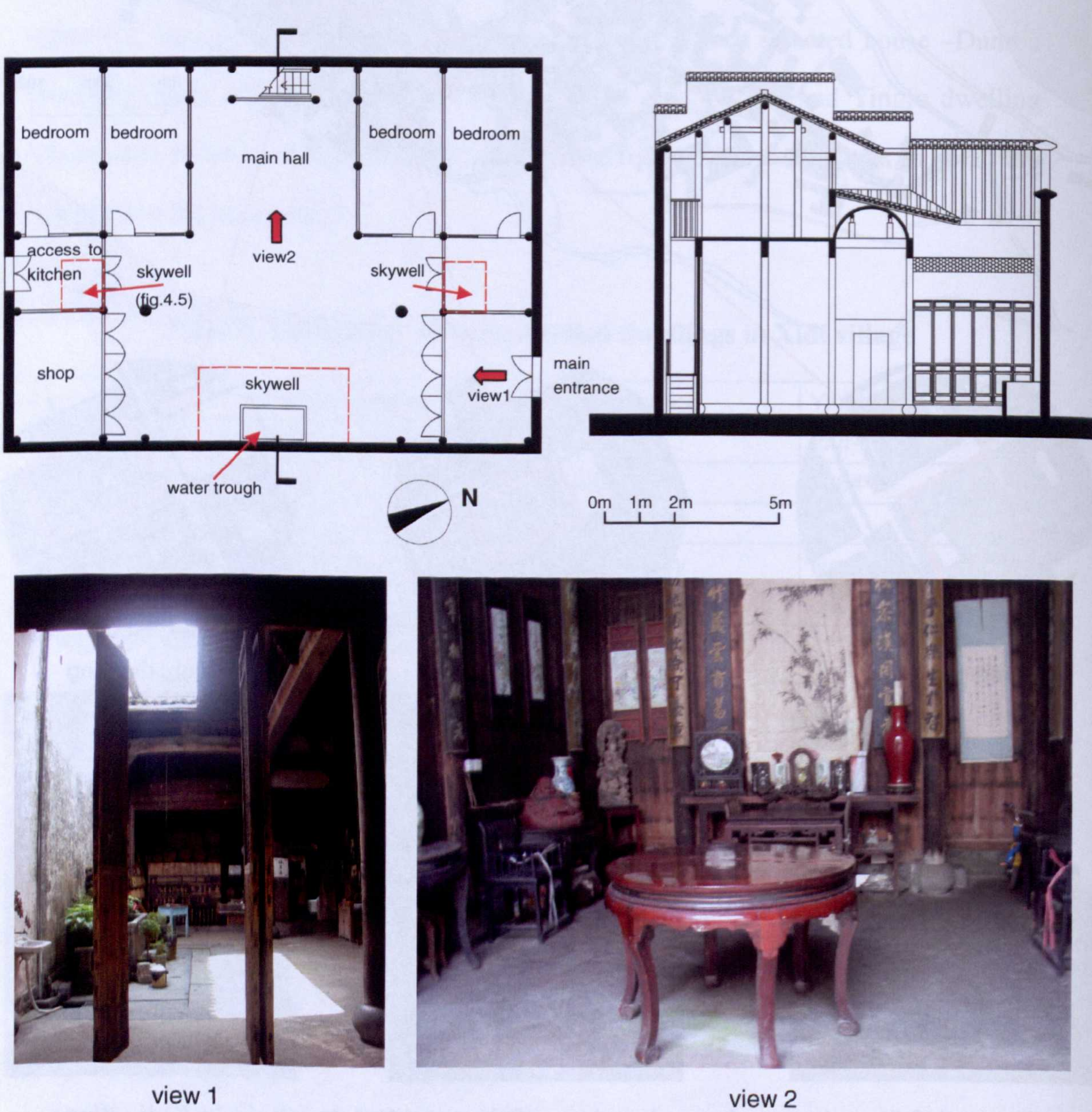


Figure 4. 4 Ground floor plan, section and views of Dunren dwelling

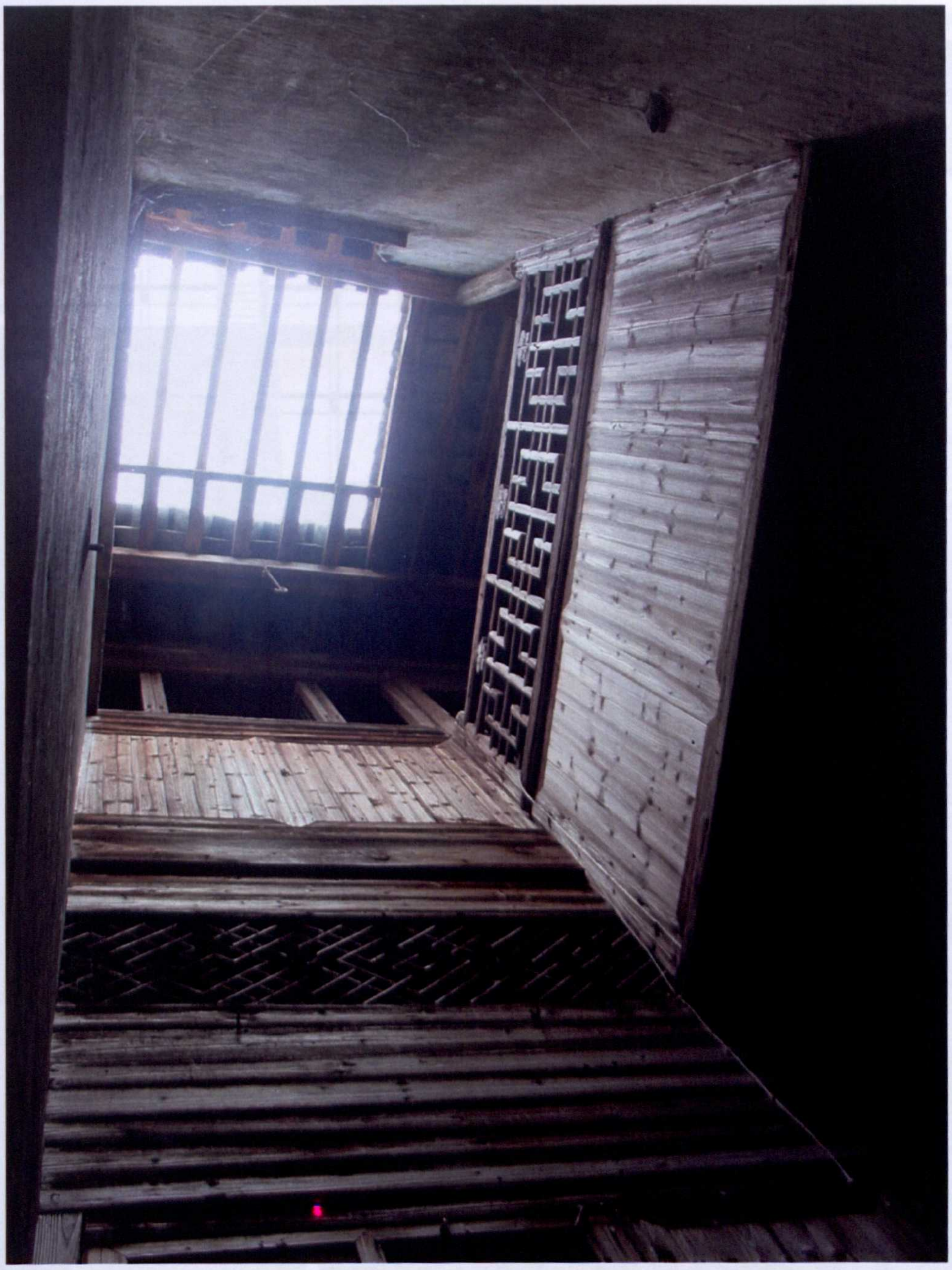


Figure 4. 5 View of a small glazed skywell in the Dunren dwelling from the ground floor

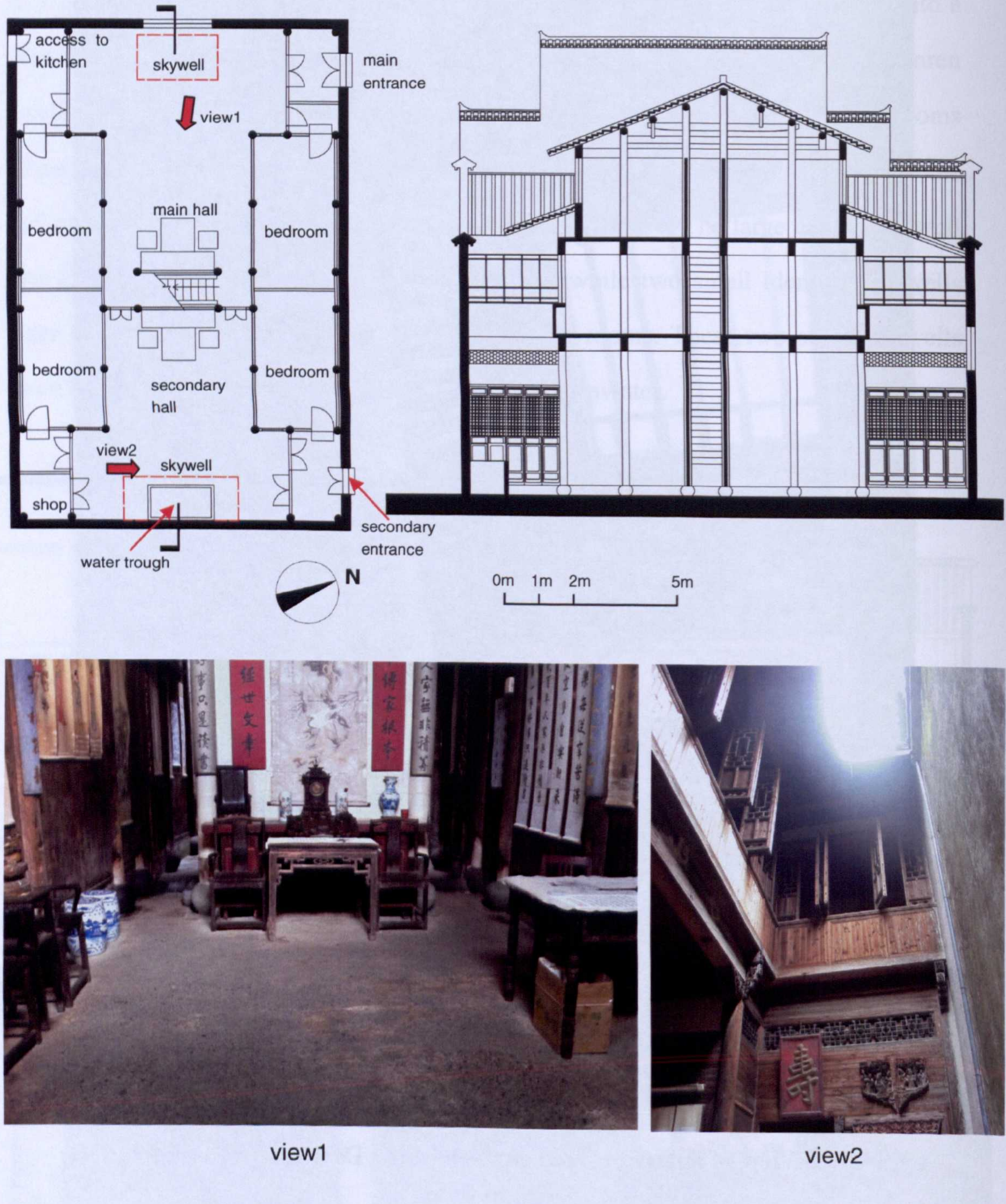


Figure 4. 6 Ground floor plan, section and views of Lufu dwelling

Xidi village has become a tourist destination in recent decades, and many residents sell souvenirs and handicrafts within their dwellings. The west side skywell of the H-shaped Lufu dwelling is glazed over to provide a rainproof space for selling goods (figure 4.7). At that time, an opening was created in the skywell wall (the wall adjoining the skywell) to provide ventilation and daylighting for the space below (figure 4.7). The opening is in the upper part of the wall for security and privacy. This opening was glazed later to prevent rain from penetrating the skywell. Opening can also be covered by a curtain when sunlight is excessive.

Figure 4. 7 West side skywell of Lufu dwelling, showing retail space and glass ceiling

In the past, the west side skywell of the house was the public space of the house and the main hall was used for formal events such as discussions and formal dinners with guests. The east side skywell was more private. Children's bedrooms are located on the east side of the dwelling. While the two skywells are directly connected by doorways (figure 4.6), children could use a secondary entrance to avoid causing disturbance in the public parts of the house. The secondary entrance, like the primary one, is located on the long north side of the building, but at the eastern end.

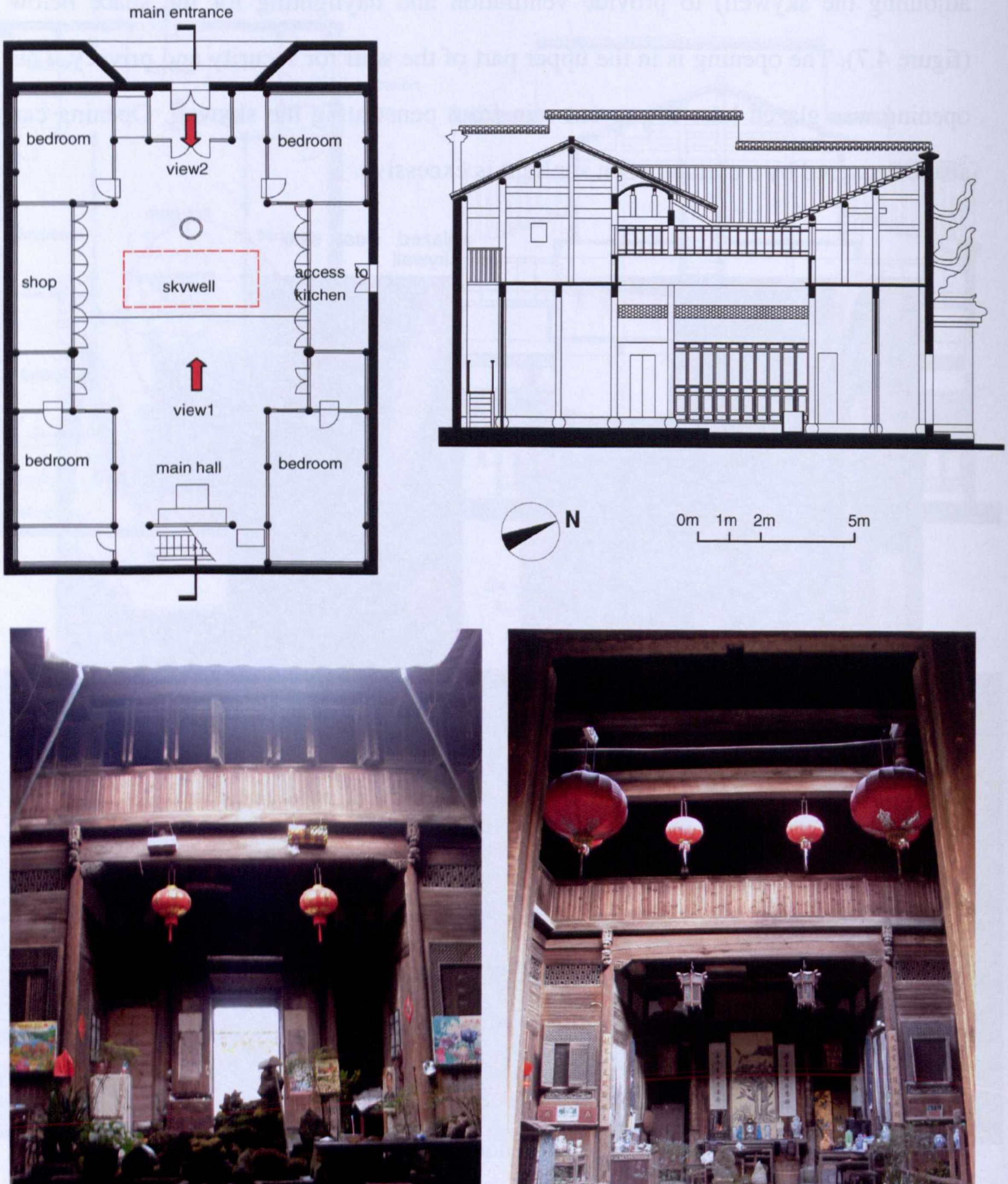


Figure 4. 8 Ground floor plan, section and views of Yingfu dwelling

The four-in-one skywell house of Yingfu dwelling can be considered as two three-in-one houses joined together face-to-face. Therefore the size of the skywell is much larger in four-in-one house than the three-in-one house.

The three dwellings studied all originally belonged to wealthy families: the Dunren dwelling was built by a famous and rich merchant named Guansan Hu; the Lufu dwelling belonged to the writer and calligrapher of Jitang Hu; and the owner of the Yingfu dwelling was a provincial governor named Shangzen Hu. Since Xidi village was originally developed by the Hu family, there were close ties of kinship between many residents of the village. For example, in the 18th century Shangzen Hu, the owner of Yingfu dwelling was a son of Guansan Hu, the owner of Dunren dwelling and was also the father of Jitang Hu, the owner of Lufu dwelling.

All three dwellings incorporate an entrance lobby (figure 4.9), which provides security and minimizes loss of heat through the entrance in cold weather.

Dunren dwelling　　Lufu dwelling　　Yingfu dwelling

Figure 4. 9 Entrance lobby of Dunren, Lufu and Yingfu dwelling

Water trough is a key feature existing in the vernacular dwellings (figure 4.10). From interviewing the local residents, the effects or supposed effects and uses of the water trough can be summarized as follows.

- Good wish to be wealthy since the water trough is used to collect the rainwater which represents collecting wealth.
- Extinguishing fires
- Improving the air quality within skywell because the dust is not easy to rise

- Raising fish and flowers by use of rainwater
- Keeping the air within the skywell cool – residents think the water is always cool in fact, this is because the water has a high heat capacity with 4176 J/kg.K and the open top trough allows evaporation

In addition, collection of rainwater in the water trough eases pressure on domestic drainage. Under the water trough water overflowing from the filled trough and rainwater falling on the skywell floor accumulates in a void space. The area of the skywell floor that lies directly under the skywell is paved with marble blocks. Water is able to drain through the gaps between the blocks into the underlying void. From the void, water is discharged to a drainage channel in the alleyway that leads to the stream.

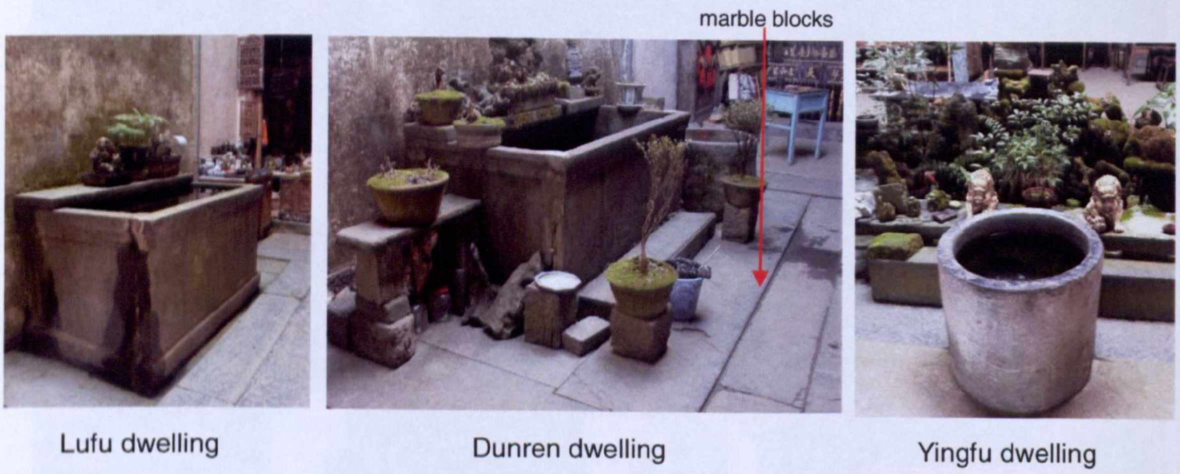


Figure 4. 10 Water troughs in Lufu, Dunren and Yingfu dwelling

In the Lufu dwelling the water trough under the west side skywell had been removed since the skywell is covered by glass. In the Yingfu dwelling, residents have removed the water trough and placed ornamental rocks and potted plants on the skywell floor instead. They have also placed a small round water trough to promote accumulation of wealth through the collection of rainwater.

4.2.2 Zhifeng village dwellings

Most skywell houses in Zhifeng village were H-shape (two three-in-one house or one three-in-one and one four-in-one house combined together).

Two typical houses – Panmaotai dwelling (H-shape) and Panxianxiong dwelling (H-shape) – were chosen for further investigation. Basic information about these monitored dwellings is summarized in table 4.2. The groundfloor plan, section and photos of each selected house – Panxianxiong dwelling (floor area 198m^2), and Panmaotai dwelling (floor area 162m^2) – are shown in the following figures.

Table 4. 2 Summary of two monitored dwellings in Zhifeng village

	Panxianxiong dwelling	Panmaotai dwelling
building type	combined three-in-one and four-in-one	H-shaped
year of built	1900s	1900s
floor area (m^2)	198	162
floors	three-storey	three-storey
no of skywell	two	two
size of skywell L X W X H (m)	south side: 1.1 X 0.75 X 6.2 north side: 1.8 X 0.75 X 6.3	east side: 1.1 X 0.6 X 6 west side: 1.1 X 0.6 X 6
area of skywell (m^2)	south side: 0.83 north side: 1.35	east side: 0.66 west side: 0.66

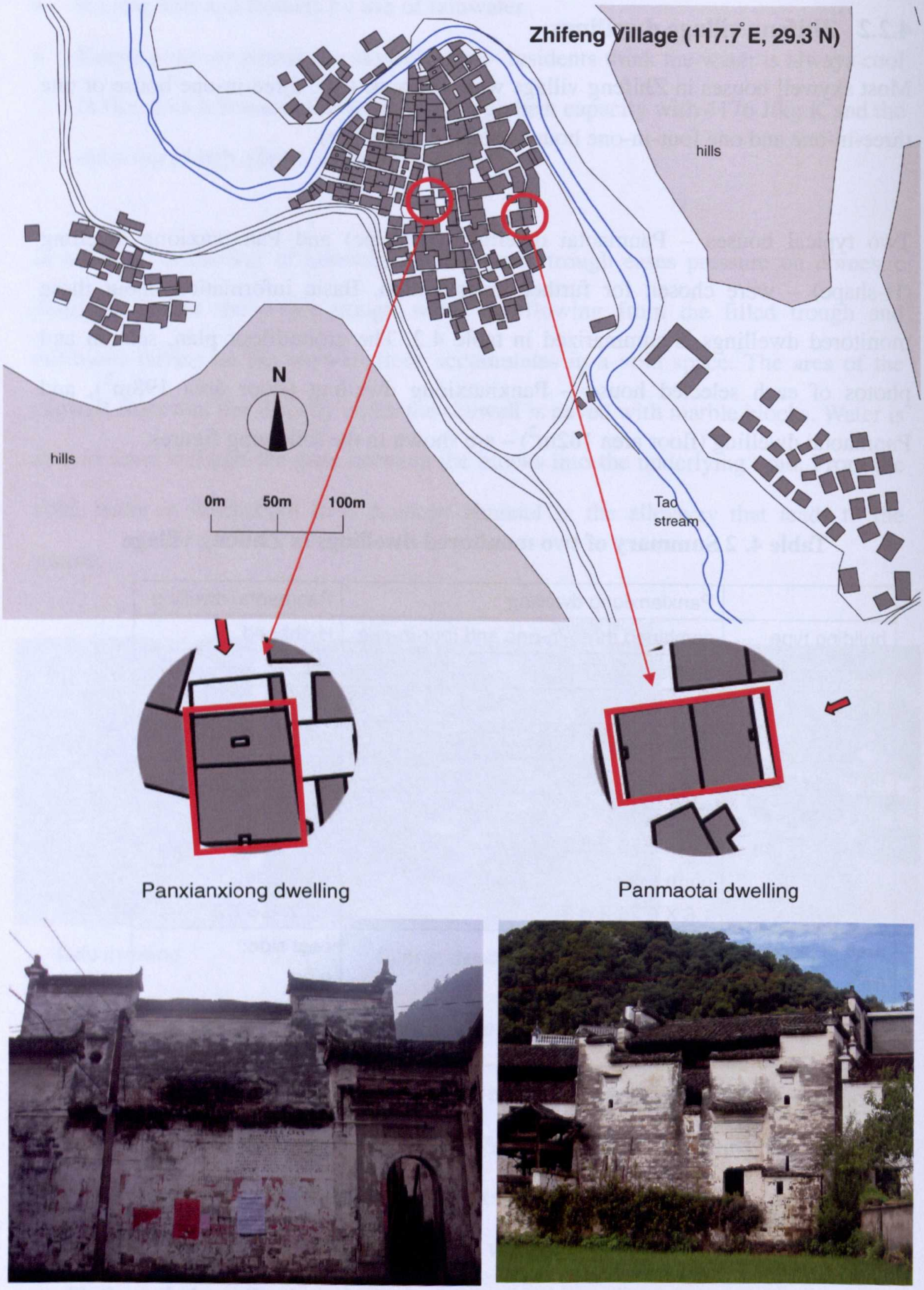


Figure 4. 11 Locations and exterior views of three typical dwellings in Zhifeng village

The Panxianxiong dwelling is not a true H-shaped dwelling but is a combination of a three-in-one and a four-in-one house (figure 4.12). This dwelling is shared by four families. There is a water trough under the south skywell. the Panmaotai dwelling is a typical H-shaped dwelling and is shared by two families. The area under the west skywell is now a kitchen area (figure 4.13).

Some features that are common in the vernacular houses of Zhifeng village are found in the Panxianxiong and Panmaotai dwellings:

- Front yards that act as buffer zones between the main entrance and the street
- A small skywell at the edge of the ceiling that combines with a small opening (approximately 1 m^2) of similar size at the top of the skywell wall to form a single opening (figure 4.13). This small opening allows sunlight to enter the skywell in winter.
- Three floor levels

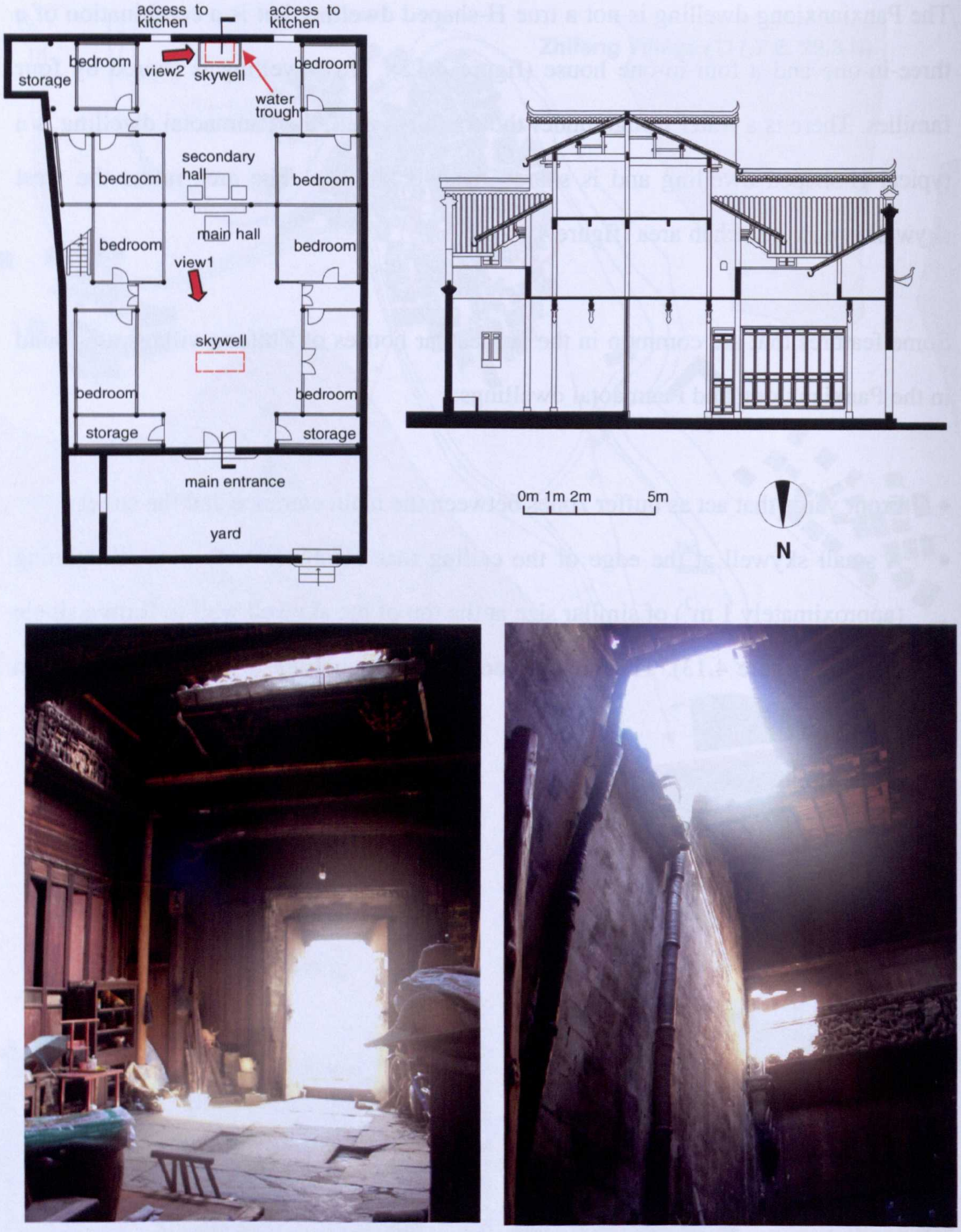


Figure 4. 12 Ground floor plan, section and views of Panxianxiong dwelling

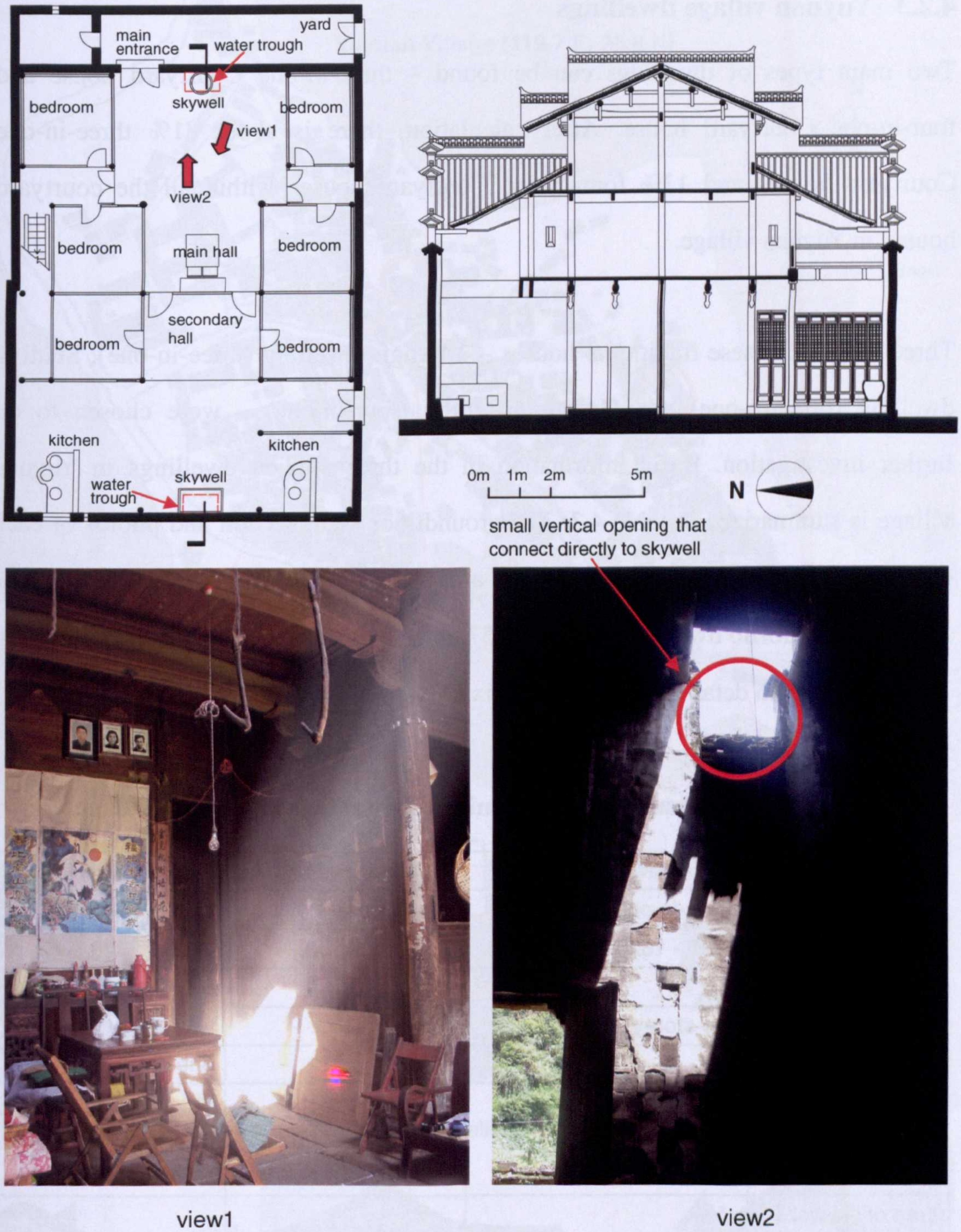


Figure 4. 13 Ground floor plan, section and views of Panmaotai dwelling

4.2.3 Yuyuan village dwellings

Two main types of dwellings can be found – three-in-one Courtyard house and four-in-one Courtyard house. After calculation, there is about 81% three-in-one Courtyard houses and 13% four-in-one Courtyard houses within all the courtyard houses in Yuyuan village.

Three typical Chinese traditional houses – Yufengfa dwelling (three-in-one), Shuting dwelling (three-in-one) and Gaozuo dwelling (four-in-one) – were chosen to do further investigation. Basic information in the three studied dwellings in Yuyuan village is summarized in table 4.3. The groundfloor plan, section and photos of each selected house – Shuting dwelling (floor area 261m^2), Yufengfa dwelling (floor area 288m^2) and Gaozuo dwelling (floor area 573m^2) – are shown in the following figures. More drawings in detail are in the appendix C.

Table 4. 3 Summary of three monitored dwellings in Yuyuan village

	Shiting dwelling	Yufengfa dwelling	Gaozuo dwelling
building type	three-in-one	three-in-one	four-in-one
year of built	1796 - 1820	1800	1796 - 1820
floor area (m^2)	261	288	573
floors	two-storey	two-storey	two-storey
no of skywell	one	one	one
size of skywell L X W X H (m)	6.1 X 5.2 X 5.3	9.2 X 2.95 X 4.9	9.3 X 5.8 X 5
area of skywell (m^2)	31.72	27.14	53.94

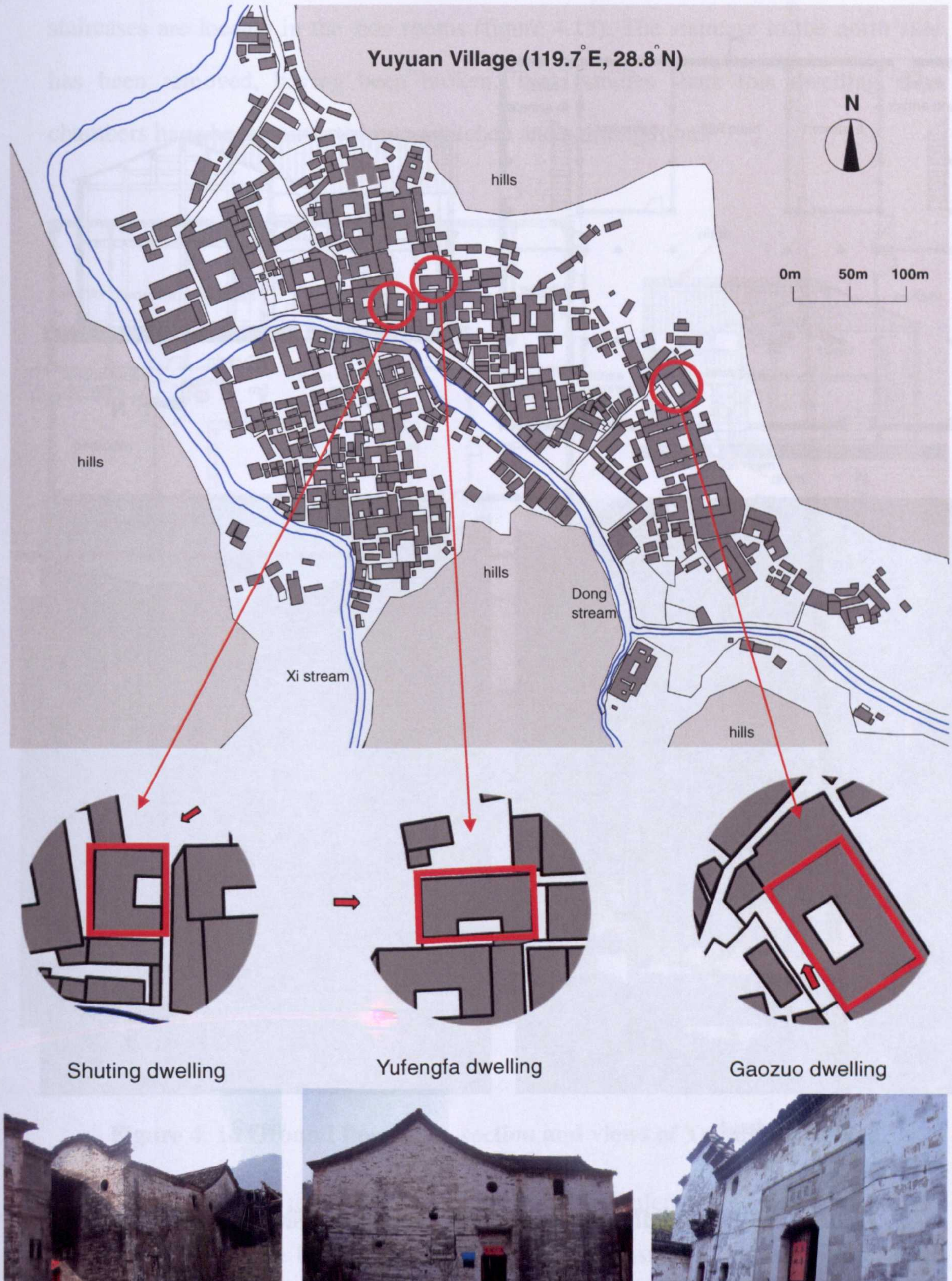
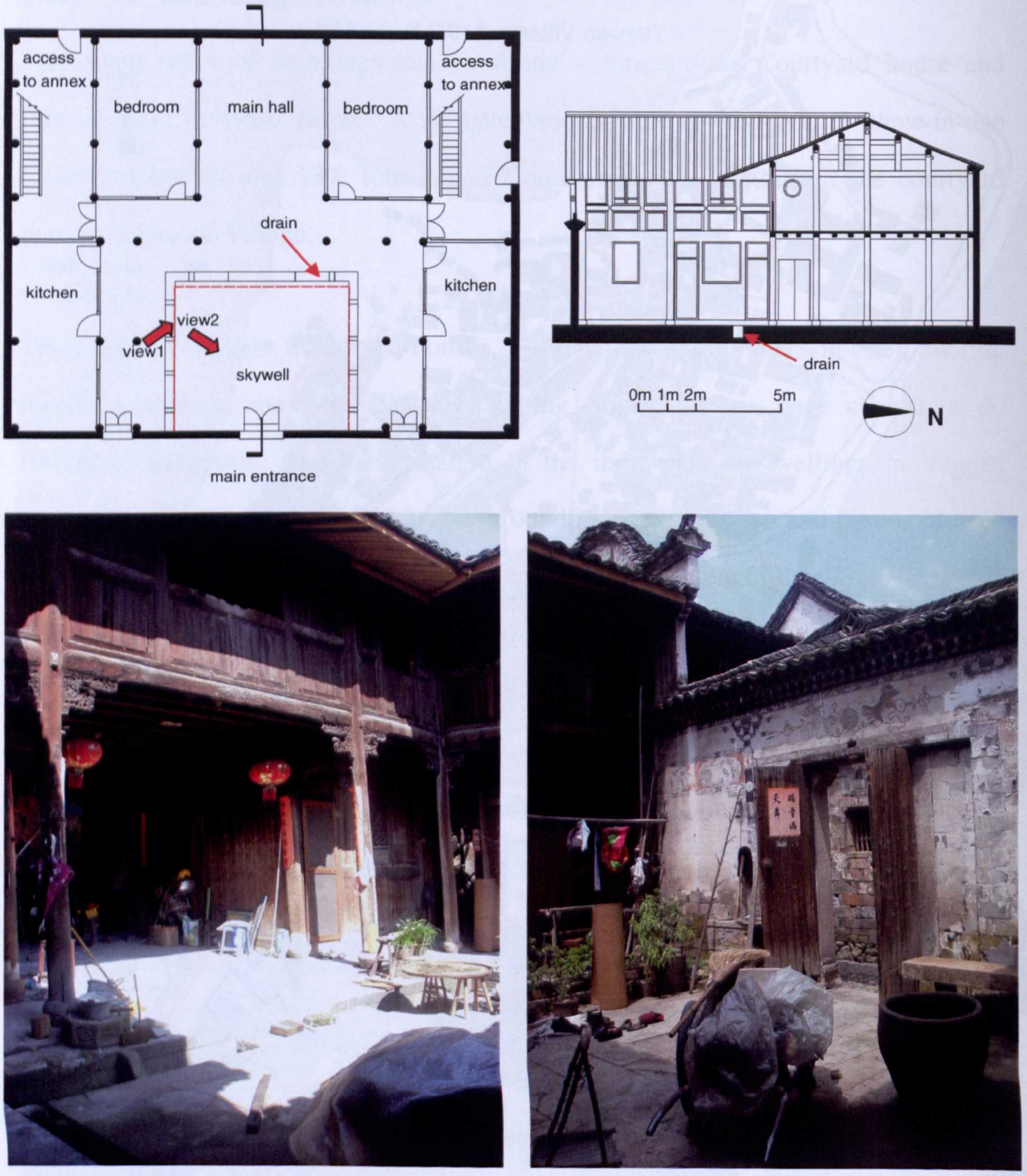


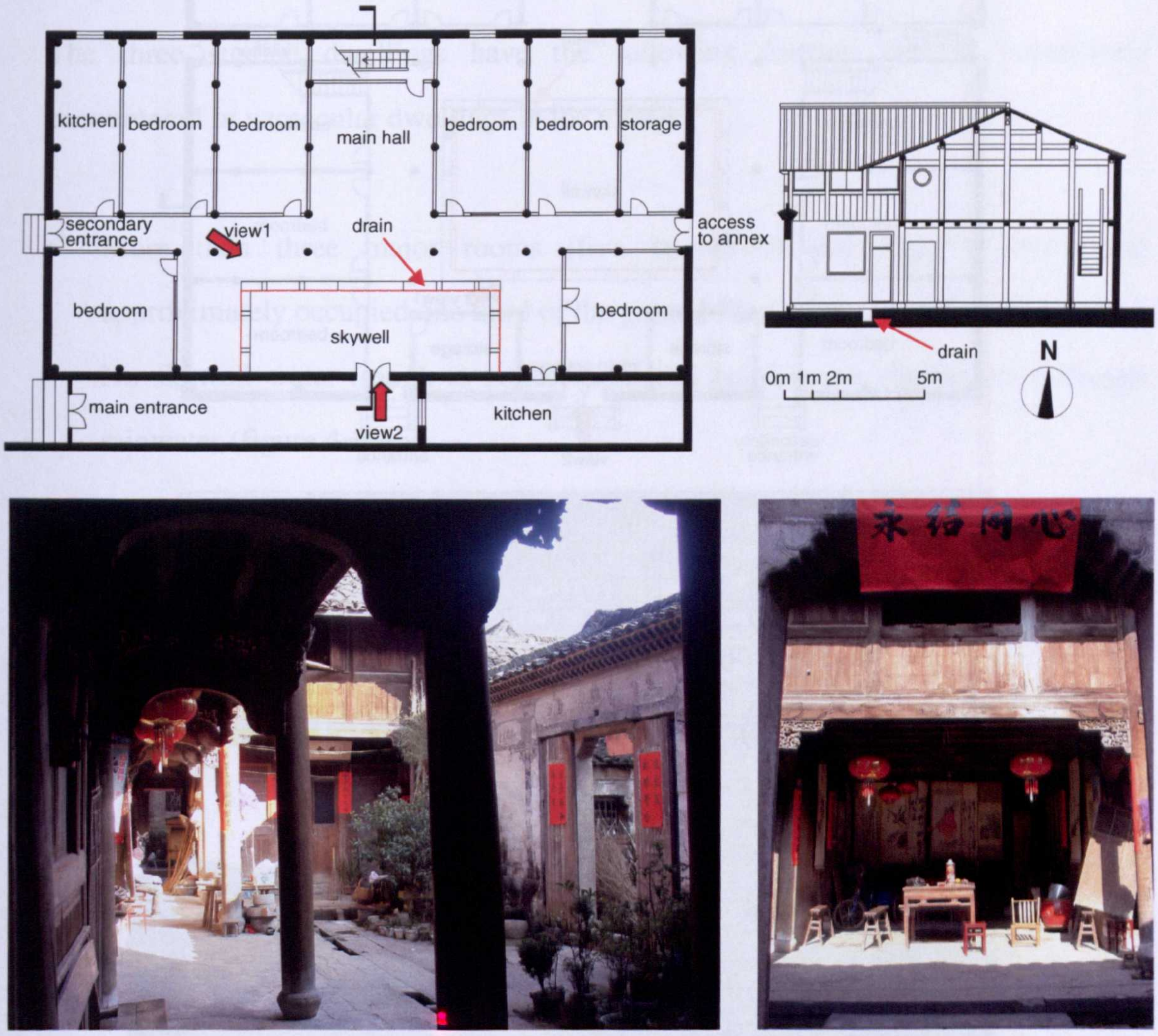
Figure 4. 14 Locations and exterior views of three typical dwellings in Yuyuan village



view1 view2

Figure 4. 15 Ground floor plan, section and views of Shuting dwelling

The skywells in Yuyuan village are large enough to be considered as courtyards. These dwellings are larger than most skywell houses (three major rooms and two chambers – chambers are secondary enclosed spaces capable of being adapted for various purposes). In the Shuting dwelling, there are five major rooms and two chambers. Two staircases are located in the side rooms (figure 4.15). The staircase in the north side has been removed, having been broken. Two families share this dwelling. The chambers have been converted into a kitchen and a dining room.



view1 view2

Figure 4. 16 Ground floor plan, section and views of Yufengfa dwelling

There are seven major rooms and two chambers in the Yufengfa dwelling (figure 4.16). The staircase is at the back of the hall, which is not usual in Yuyuan village. Four families share this dwelling. One family has built a kitchen at one end of the now-enclosed alleyway between the front of the house and the dwelling opposite. Another family uses a corner room of the house as their kitchen, while two other families use an ancient detached annex kitchen for cooking.

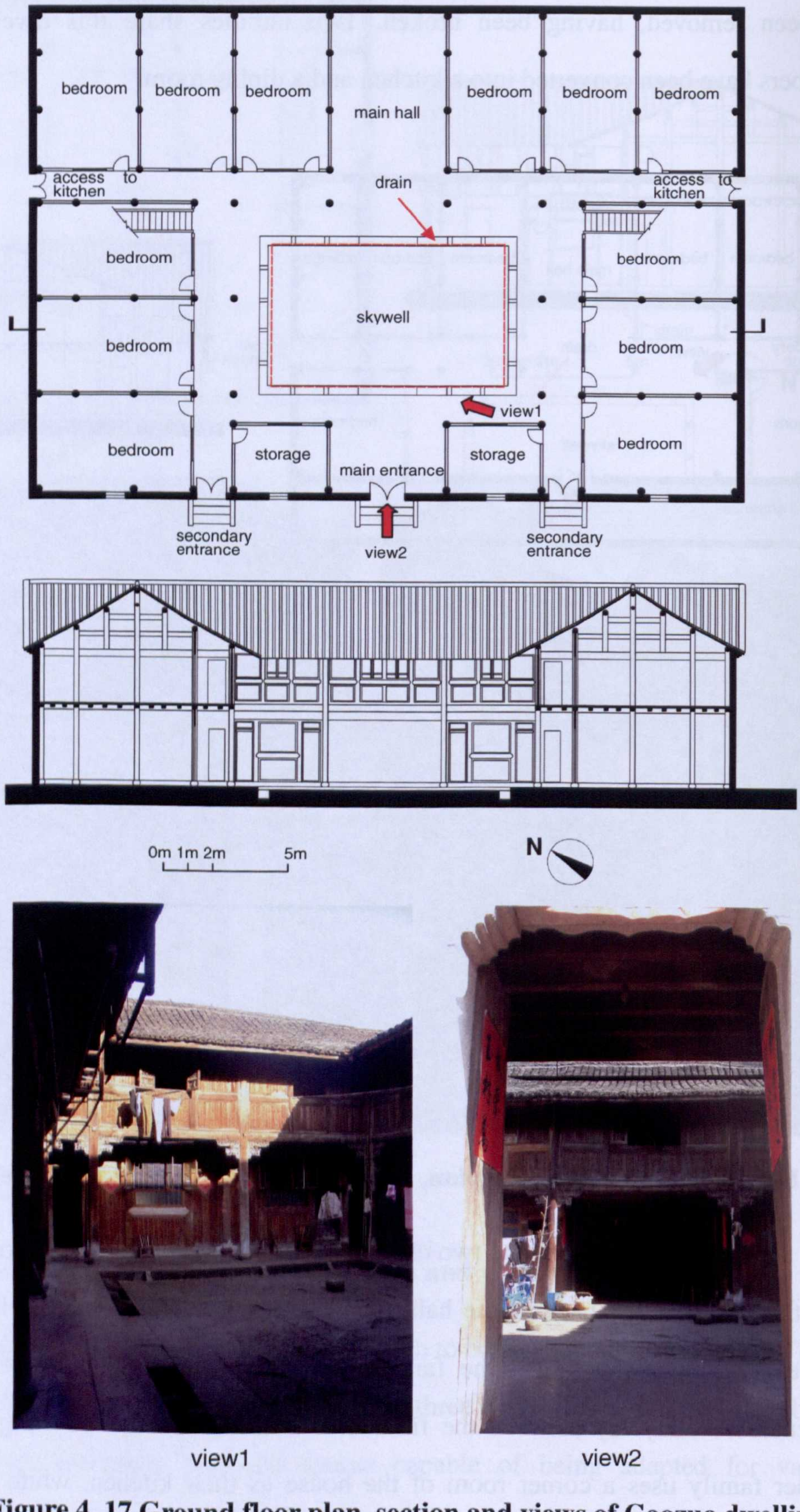


Figure 4. 17 Ground floor plan, section and views of Gaozuo dwelling

Gaozuo dwelling is the largest of the eight dwellings studied. It has seven major rooms and six chambers, and is shared by nine families (figure 4.17). Two staircases are located besides the chambers at the mid-left and mid-right of the building.

The three studied dwellings have the following features that are commonly encountered in vernacular dwellings in the village.

- More than three major rooms (five or seven) and large skywells that approximately occupied one third of the ground floor area.
- No skywell water trough to collect rainwater but a water channel to discharge rainwater (figure 4.18).

Figure 4. 18 Water channel in Gaozuo dwelling

- Two symmetrically opposed staircases, in either the chambers or the side rooms.
- No entrance lobby and a main entrance that leads directly into the main hall.

4.3 Summary

The eight dwellings fall into three categories of vernacular house design – three-in-one, four-in-one and H-shape. In each dwelling the core of the layout is a skywell, with accommodation on three or four sides (three-in-one or four-in-one house). The skywell and a hall opening into the skywell both lie on the central axis of the ground plan. The eight skywell houses consist of either two or three floors and all have the typical white projecting horse-head wall. The principal materials used in creating a Chinese vernacular dwelling are as follows:

- Wood (Chinese fir), used to make wall panels, column and the overhanging frames supporting eaves tiles.
- Brick, in two 2 cm layers enclosing a wide void (26 cm) filled with mud and sand stones of various sizes to form the external walls
- White lime, used to paint the walls (with many patches of grey discolouration and green algae growth)
- Stone, used to pave the area at the foot of the skywell where the water trough is located
- A blend of finely divided materials used to create the floor around the edges of the skywell floor under the roof overhang. Different mixtures were used; mixtures might include sand, while lime, small stones, tung oil or rice slurry.
- Fired clay, used to make the roof tiles of the overhang eaves.

In traditional Chinese culture the direct revelation of important matters is considered ill-mannered and socially undesirable, while privacy is valued. These beliefs are reflected in domestic architecture. The hall of a dwelling is the site of familial interaction, and is the place where important guests may be entertained; accordingly, the hall should not be observable by outsiders. In Xidi village, in the three-in-one skywell house the skywell abuts an outer end wall of the house and the hall is close to that outer wall; in the Lufu house the centre of the hall is 5 m from the skywell wall, while in the Dunren house the corresponding distance is 8 m. Since these distances are short, in these dwellings the main entrance is not cut into the skywell wall at one end of the house, but into one of the long exterior walls, close to a corner of the building. Passers-by would be able to see into the skywell through a small lobby space but not into the hall, which is further down the long axis of the building. In the Yingfu dwelling the main entrance is cut into the middle of an end wall. The skywell is in the centre of the house and the main hall is at one end of the building, away from the main entrance. Although sight lines allow the main hall to be viewed from the entrance, the distance from the entrance to the centre of the hall is 12 m, which is sufficient to prevent clear observation of the hall by passers-by.

In Zhifeng village, most dwellings have front yards as a buffer zone in front of the main entrance. This prevented passers-by seeing into the house. In the larger houses in Yuyuan, the main entrance leads directly into the main hall. Many adult males would be present running home-based business, so there was less need to ensure privacy and security through house design.

The differences between the eight dwellings within the three villages studied and the local characteristics they exemplify can be summarized as follows.

House sharing arrangement

In Xidi village, one family owns one skywell house while in Zhifeng and Yuyuan villages; each skywell house is shared by several families. This is due to land and property reform in the early 1950s. Accommodation was reallocated according to local need, with two or more families being placed in some larger dwellings.

Water trough

Water troughs are common in the vernacular houses of Xidi and Zhifeng villages but are absent from houses in Yuyuan village. Rainwater is discharged from the skywell by a covered drain in Xidi and Zhifeng villages, but by a water channel in Yuyuan.

Horse-head wall

There are horse-head walls in four sides of the vernacular dwellings in Xidi and Zhifeng. In Yuyuan village there is only one side horse-head wall incorporating the main entrance.

Position of staircase

The staircase is normally placed at the back of the hall in Xidi village, while in Zhifeng and Yuyuan villages, the staircase is at the side of the dwelling. In Yufengfa dwelling (Yuyuan village) the staircase is at the back of the hall. In Xidi and Zhifeng villages, there is only one staircase in each house while in Yuyuan village, there are normally two positioned symmetrically about the central axis of the skywell and the open hall.

Veranda

Verandas are a common feature of the vernacular dwellings of Yuyuan village but are absent from houses in Xidi and Zhifeng villages.

Column bases

Round bases of wooden columns can be found in Xidi and Yuyuan villages while cube bases are found in Zhifeng village (figure 4.19).

Figure 4. 19 Base type in Xidi village (left), Yuyuan village (middle) and Zhifeng village (right)

Many of the finely carved wooden panels in the houses of Zhifeng village had been sold by residents before the local government started to protect them. These wooden panels were replaced by three-ply board, which harmed the appearance of the whole house (figure 4.20). Removal of original panels and various other forms of remodelling of vernacular dwellings is now forbidden by law.

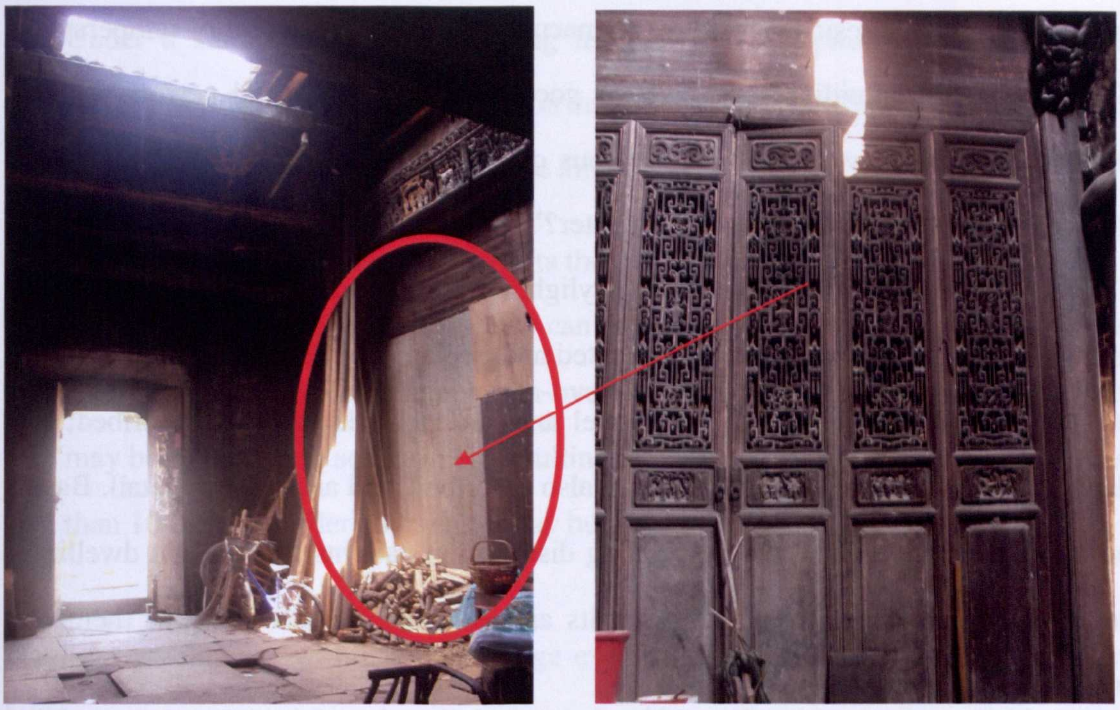


Figure 4. 20 Finely carved wooden panel from Panmaotai dwelling (right), and location in Panxianxiong dwelling in which a similar panel would originally have been present (left). The panel that would have occupied that space has been sold.

5 DAYLIGHTING PERFORMANCE

5.1 Introduction

The aim of the work described in this chapter is to answer research questions 4 'How comfortable are the residents of these vernacular dwellings in respect of temperature, illumination and humidity?' and 5 'How good is the environmental performance of skywell dwellings, as assessed by rigorous quantitative analysis of daylighting and thermal performance in summer and winter?' in respect of daylighting performance. The results of the questionnaire about daylighting performance are given first. Some terms used in the analysis are then presented and explained. The method used to carry out the measurement of illuminance level and surface reflectance is described; the daylighting data obtained in the study are also described, and analyzed in detail. Based on these illuminance data, the daylighting distribution patterns of the eight dwellings are generated. A discussion of the results and conclusions derived from them are presented at the end.

Residents' satisfaction with the daylighting level in traditional houses of Zhifeng village was low, with a mean score of 2.6 (Scores were reported on a scale of 1 to 5, in which 1 indicated 'very dissatisfied', 3 indicated a neutral response and 5 indicated 'very satisfied' – see section 1.3.1). In Xidi village, the mean satisfaction was 3.6, while in Yuyuan residents returned the high mean score of 4.5. This is easy to understand – the skywells of the dwellings in Zhifeng village are small, those of the Xidi dwellings are moderate in size, while those of the dwellings in Yuyuan are large. The mean proportions of the ground plan occupied by the skywell in the dwellings studied in Zhifeng, Xidi and Yuyuan were 1.4%, 5.7% and 12.8% respectively; thus, reported satisfaction rose with increasing proportion of ground plan occupied by void area. When describing the methods to improve the daylight level within a dwelling, some respondents explained that they felt there was no need to improve the daylight level in the bedroom, because the bedroom is only for sleep and they carried out most of their activities in the skywell area and the hall.

Data on daylighting performance of the houses were collected on overcast days for the following reasons:

- Under a sunny sky, the daylighting level within a skywell dwelling changes rapidly. Under these conditions it is impossible to identify the relationship of daylighting performance between the interior and exterior of a skywell dwelling.
- The overcast sky condition represents the worst condition for the accomplishment of visual tasks. If a visual task can be undertaken on overcast days, the illumination available on sunny non-overcast days will be at least sufficient (but may be excessive at some times, resulting in glare). Sky illuminnace could be less than 10 000 lux under an overcast day but around 100 000 lux on a sunny day.

Daylight levels vary within a wide range even on an overcast day, but indoor light level as a percentage of outdoor light level should remain constant over a wide range of outdoor light levels. Indoor light level as a percentage of outdoor light level is termed the daylight factor (DF). DF was used as the principal measure of daylighting performance in the present study because of its invariance under overcast sky conditions.

The mean daylight factor (DF_m) was calculated as the mean DF values measured at different spots evenly distributed within certain area. An DF_m of 5% or more will result in a bright daylit effect while this value below 2% could lead to poor daylight conditions (Tregenza and Loe, 1998). Table 5.1 below gives some useful guideline figures.

Table 5. 1 Room appearance and average daylight factor (Source: Tregenza and Loe, 1998)

average daylight factor	room appearance
5% or more	The room has a bright daylit appearance. Daytime electric lighting is usually unnecessary. High levels of daylight may be associated with thermal problems.
2-5%	The room has a daylit appearance but electric lighting is usually necessary in working interiors. It could be required to enhance illuminance on surfaces distant from the window and to reduce contrast with the view outside. The use of daylight with supplementary electric lighting is often the best choice for practicality and energy efficiency.
below 2%	Electric lighting is necessary, and appears dominant. Windows may provide an exterior view but give only local lighting.

DF_m describes the overall daylight appearance of a space, but it neglects daylight distribution, which is also important (Littlefair and Aizlewood, 1998). Deep narrow rooms can seem too gloomy at the back even though DF_m is adequate (above 2%). Such rooms have a small uniformity ratio (UR) - the ratio of the minimum DF to DF_m (CIBSE, 1999).

Some terms used in the analysis of the eight vernacular dwellings studied are explained below.

$DF_{m,sky}$ – mean of DF values that were calculated directly under the skywell. The red area in figure 5.1 below indicates the area in which individual illuminance measurements were taken. $DF_{m,sky}$ was calculated from these values.

$E_{m,sky}$ – mean of illuminance values that were measured directly under the skywell.

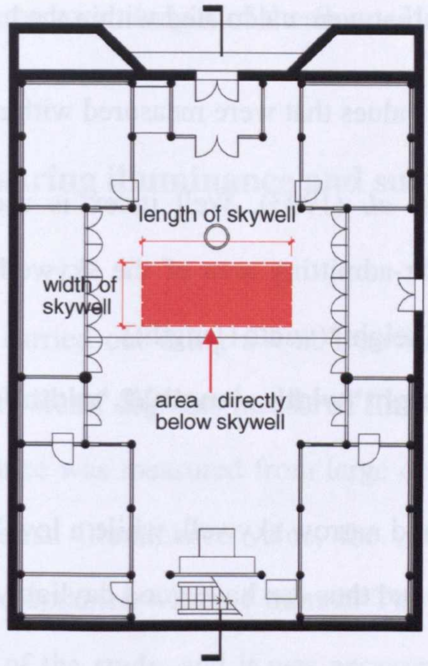


Figure 5. 1 Area directly under skywell in which DF values were obtained for calculation of $DF_{m,sky}$ (area shown in red)

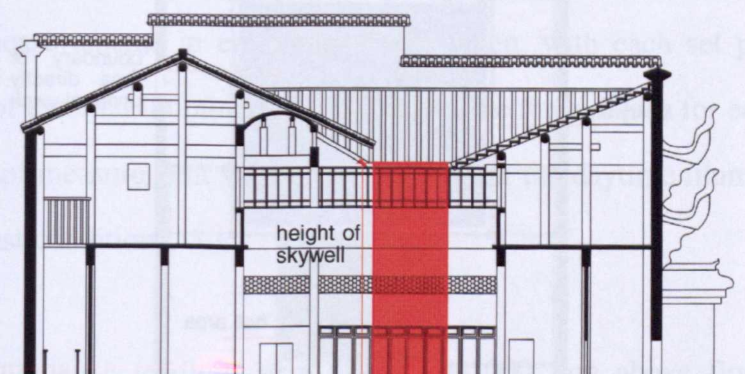


Figure 5. 2 Section through dwelling, showing skywell (red). Area at 1m above foot of skywell is area in which DF values were obtained for calculation of $DF_{m,sky}$

$DF_{m,uti}$ – mean of DF values that were calculated over the whole of the utility area (figure 5.3)

$E_{m,uti}$ – mean of illuminance values that were measured over the whole of the utility area

$DF_{m,hall}$ – mean of DF values that were calculated within the hall area (figure 5.3).

$E_{m,hall}$ – mean of illuminance values that were measured within the hall area.

WI – according to Baker *et al.* (1993), Well index is used here to describe the relationship between the light-admitting area of the skywell (length*width) and the area of the skywell surfaces (height*(width+length))

WI= height*(width +length)/2 *width*length

A high WI represents a tall and narrow skywell, while a low WI means the skywell is wide compared to its height, and thus can have good daylight conditions.

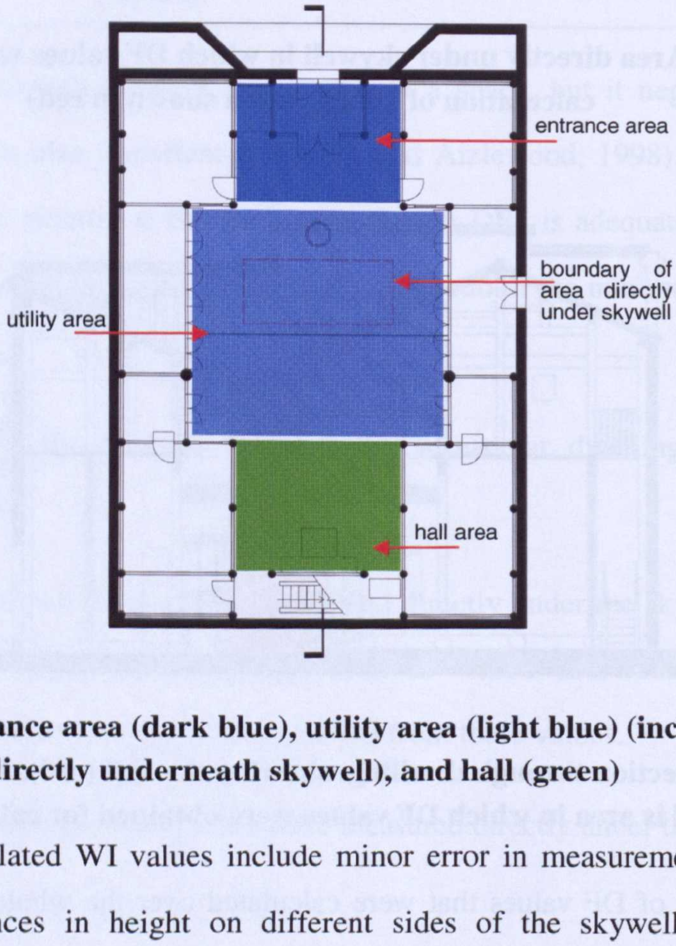


Figure 5. 3 Entrance area (dark blue), utility area (light blue) (including area directly underneath skywell), and hall (green)

Inaccuracy in calculated WI values include minor error in measurement of skywell height and differences in height on different sides of the skywell necessitating approximation in assigning a height value. Most of the skywells studied had sides which did not reach to the same height. When a skywell has three or more sides of the same height, that height was used calculating the WI. Where no more than two sides were of the same height the mean height of the floor sides was used to calculate the WI.

5.2 Method of measuring illuminance and surface reflectance

5.2.1 Daylighting level

Illuminance testing was carried out using a 4-in-1 environment meter. The external illuminance level of the overcast day was measured first before inside measurements were taken. Sky illuminance was measured from large open spaces (village squares). Having obtained an external illuminance value, the corresponding internal values within a given room were obtained within 1 minute. The present author was the sole field worker in this part of the study, and it was necessary for him to obtain sets of measurements by moving from the external measurement point to the room as quickly as possible. Ideally, internal and external illuminance values would have been obtained simultaneously, by using a pair of field workers. At least 3 complete sets of illuminance measurements in each room were taken, with each set preceded by a measurement of external illuminance; the mean of the three values for each internal or external point of measurement was taken to represent the daytime illuminance at that point in overcast conditions.

Horizontal illuminance readings at a height of 1000 mm above floor level were recorded from each floor of the dwellings. For each floor an approximate grid of measurements was obtained in each of the three sets of measurements. Measurements were obtained from points which were spaced evenly between columns – the columns were arranged symmetrically in all the dwellings studied. After processing of illuminance data, daylighting contours were generated using the software package Surfer 9 (Golden Software Inc., USA). The daylight distribution within the eight dwellings studied is shown in detail in section 5.3.

5.2.2 Surface reflectance

The surface reflectance of vernacular dwellings was measured by a photometer. After testing the luminance of a particular surface material of a vernacular dwelling, the result was recorded as L_s. The referent (A4 paper) was placed in the same position as the surface previously measured, and tested; the result was recorded as L_r. The reflectance of that surface, η_s, would then be calculated using the following equation in which $\eta_r = 0.9$.

$$\eta_s = \frac{\eta_r \ L_s}{L_r}$$

This procedure was carried out two or more times for each surface material, using readings taken at different points on the surface of the material. Each pair of material / white paper readings was obtained at a different point on the material's surface. Mean values of surface reflectance were derived from the individual values of surface reflectance calculated at the different points. The calculated mean values of surface reflectance of the different surface material are shown in table 5.2 below. These materials all had diffuse, matt surfaces.

Table 5. 2 Surface reflectances of building material of vernacular houses in the three villages studied

surface material or structure component of the dwellings	mean surface reflectance
skywell wall	0.56
wooden panel	0.35
floor	0.47
ceiling	0.13

5.3 Daylighting performance of dwellings in Xidi village

The vernacular dwellings in Xidi village have high horse-head walls and few small openings (or without openings) on the walls for security reasons. Daylight for the skywell floor is entirely from the skywell – if the door is closed – while the illumination of the bedrooms on the ground floor is entirely from the window facing to the skywell (figure 5.4).

Figure 5. 4 Large opening of skywell and small opening of bedroom facing to the skywell in Yingfu dwelling

The DF isolux contours on different floor levels in Yingfu Hall are shown in the following figures.

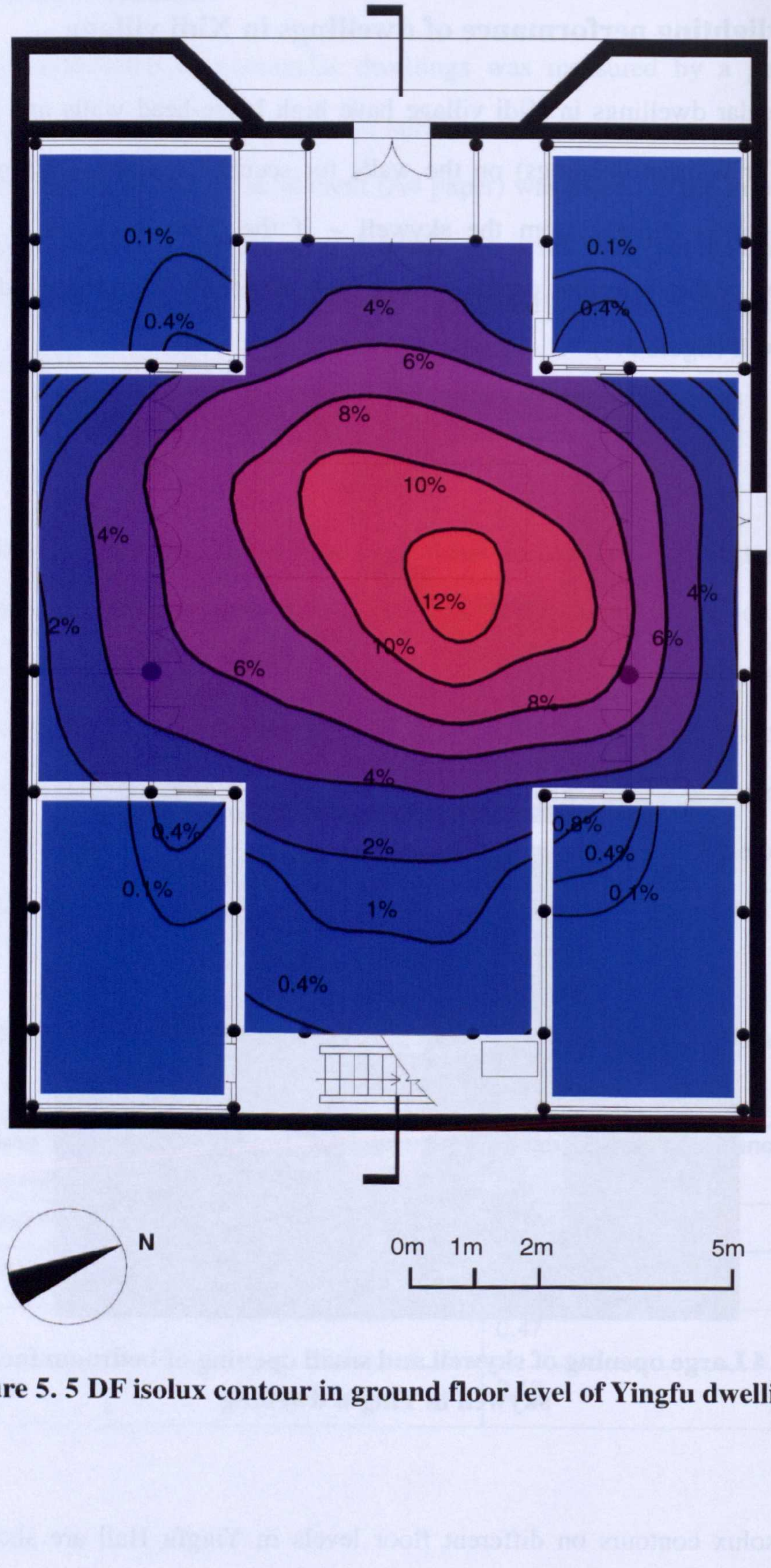


Figure 5. 5 DF isolux contour in ground floor level of Yingfu dwelling

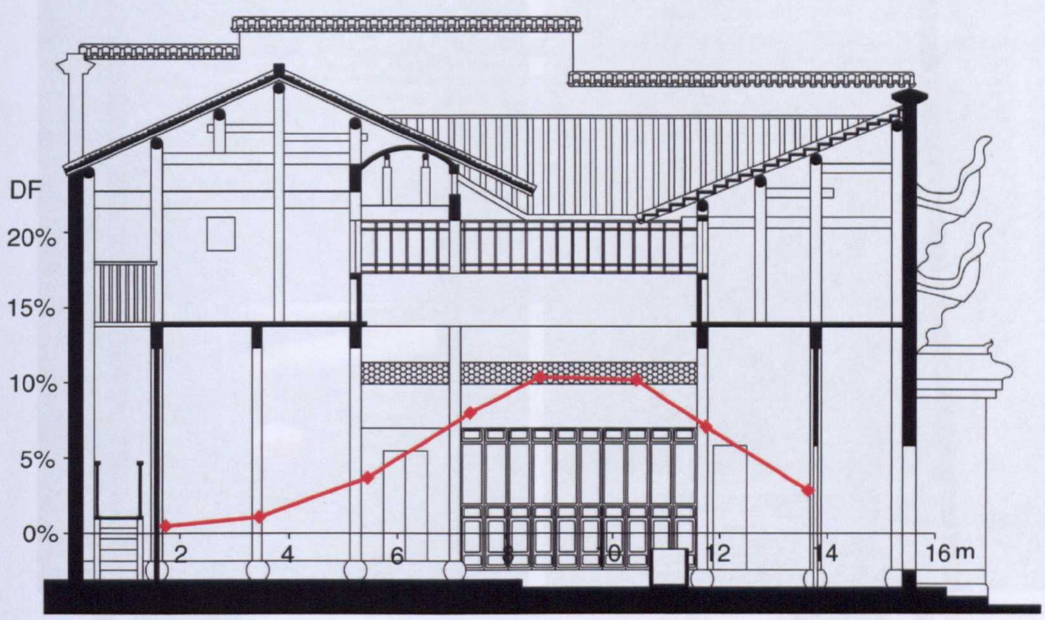


Figure 5. 6 Section showing DF at 1m above ground floor level of Yingfu dwelling

The area directly below the skywell in the central area of Yingfu Hall and the adjoining utility area received adequate daylight but the hall area did not. Within the Yingfu dwelling, $DF_{m,sky}$, $DF_{m,uti}$ and $DF_{m,hall}$ were 10%, 7.4% and 1.9% respectively.

Daylighting levels within the bedrooms in the four corners of this house were very low. For example, in the bedroom in the southeast corner of this house the maximum DF, obtained near the window was only 0.8%, while the area of the room furthest from the window was found to almost no light. The interior of GF bedrooms in this house were always gloomy, because they have only one window facing into the skywell. With openable wooden shutters in a highly ornamental concentric lattice design, whether the shutters were open or closed, the windows admitted little light (figure 5.7).

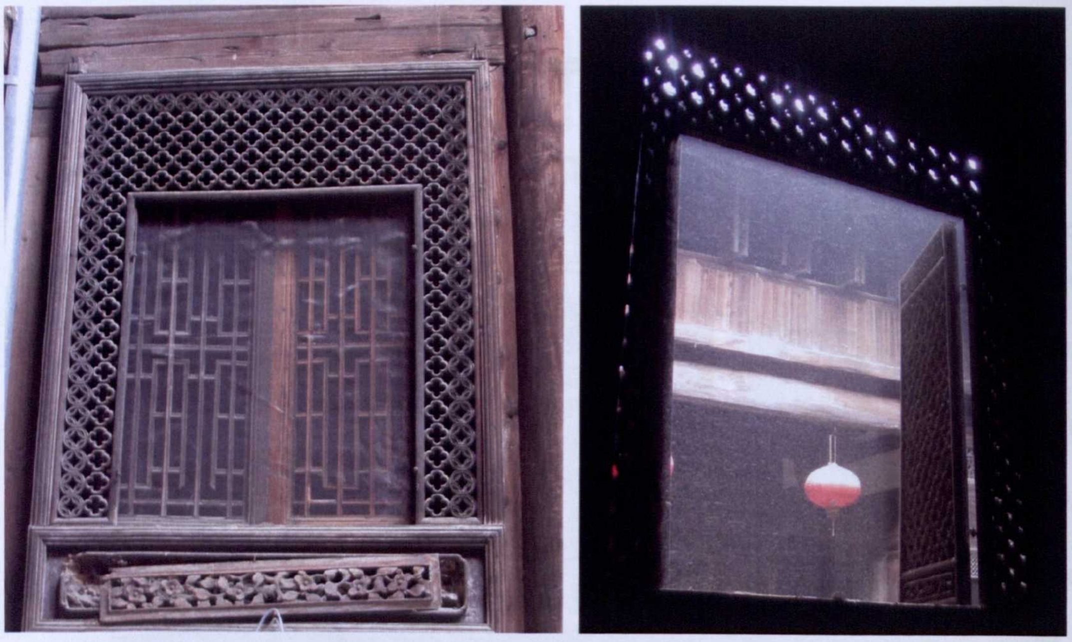


Figure 5. 7 External and internal view of window in Yingfu dwelling

Traditionally, bedrooms were regarded as sleeping areas which were only occupied during the night, so abundant illumination of these spaces was not considered a necessity. In the daytime, residents have always spent most of their time in the hall and the skywell, which together have been used as living spaces.

As indicated in figure 5.8, the first floor of Yingfu dwelling is very gloomy with mean DF 0.1%. With only four small unglazed openings in the external wall (see figure 5.9) and a roof large overhang not far above the window which excludes a lot of light, the maximum DF on this floor was only 2.1%. In the past, there were bedrooms at the four corners of the dwelling – the small openings provided limited daylight and ventilation. The south-east window admits much less light than the other three windows because another dwelling is very close to the Yingfu dwelling on that side, with an alley only 1m wide between them. Most of the light from this side is blocked by the nearby building.

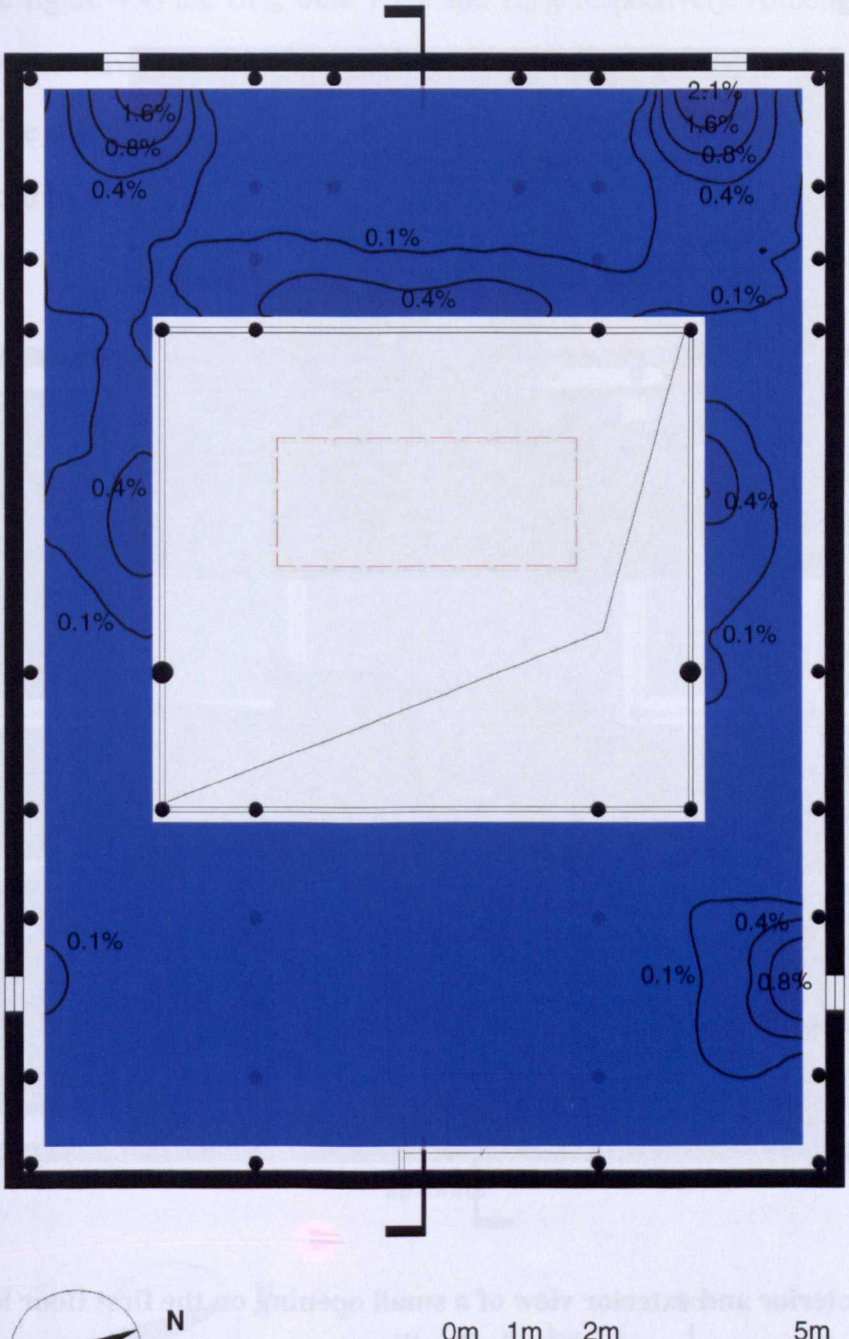


Figure 5. 8 DF isolux contour in first floor level of Yingfu dwelling

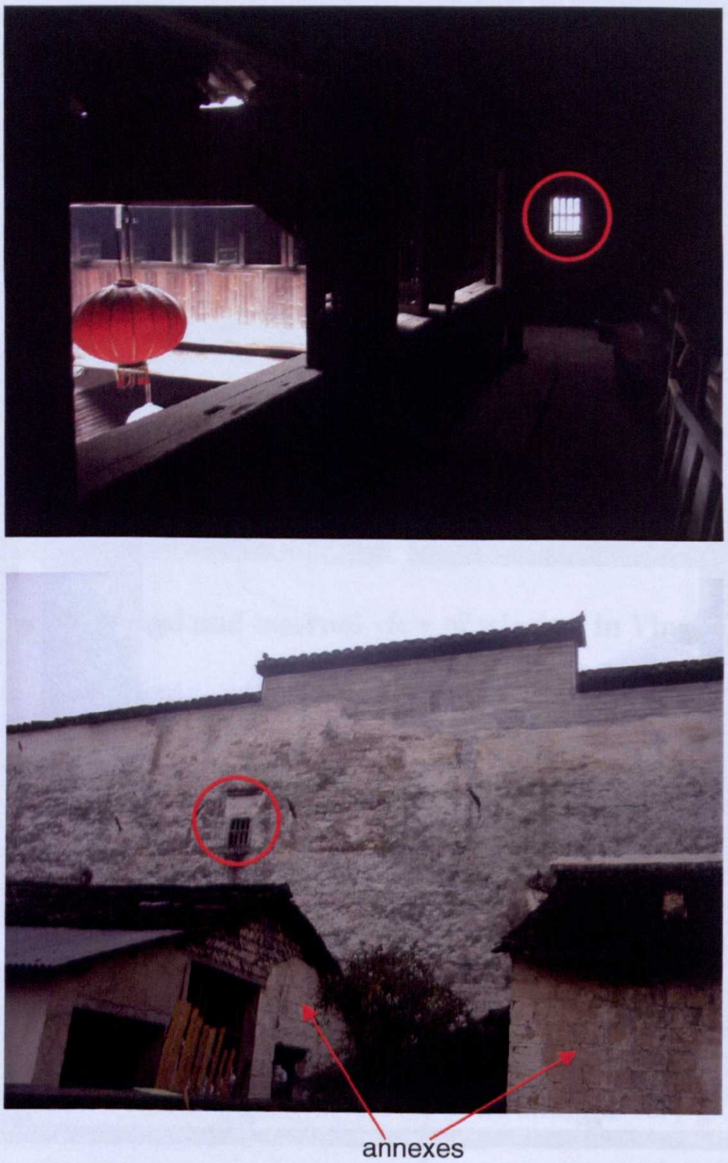


Figure 5. 9 Interior and exterior view of a small opening on the first floor level in Yingfu Dwelling

Since the spaces on the first floors of the dwellings are disused or used for storage, and the residents mainly stay in the hall and the skywell during the daytime, the DF on the skywell floor and in the hall will be the focus of discussion related to other dwellings. DF pattern on the ground floor in each studied dwelling is described below.

In the Dunren dwelling, the $DF_{m,sky}$ and $DF_{m,uti}$ was 14.4% and 6.2% respectively. The $DF_{m,hall}$ was 0.7%, while under the two identical small skywells (south side and north side, see figure 4.4) the DF_m were 1.1% and 1.3% respectively. Although both of the two skywells have been glazed, the north side skywell was not glazed until the year of 2009. The different daylighting level was due to the difference in the transmittance influenced by glass cleanliness.

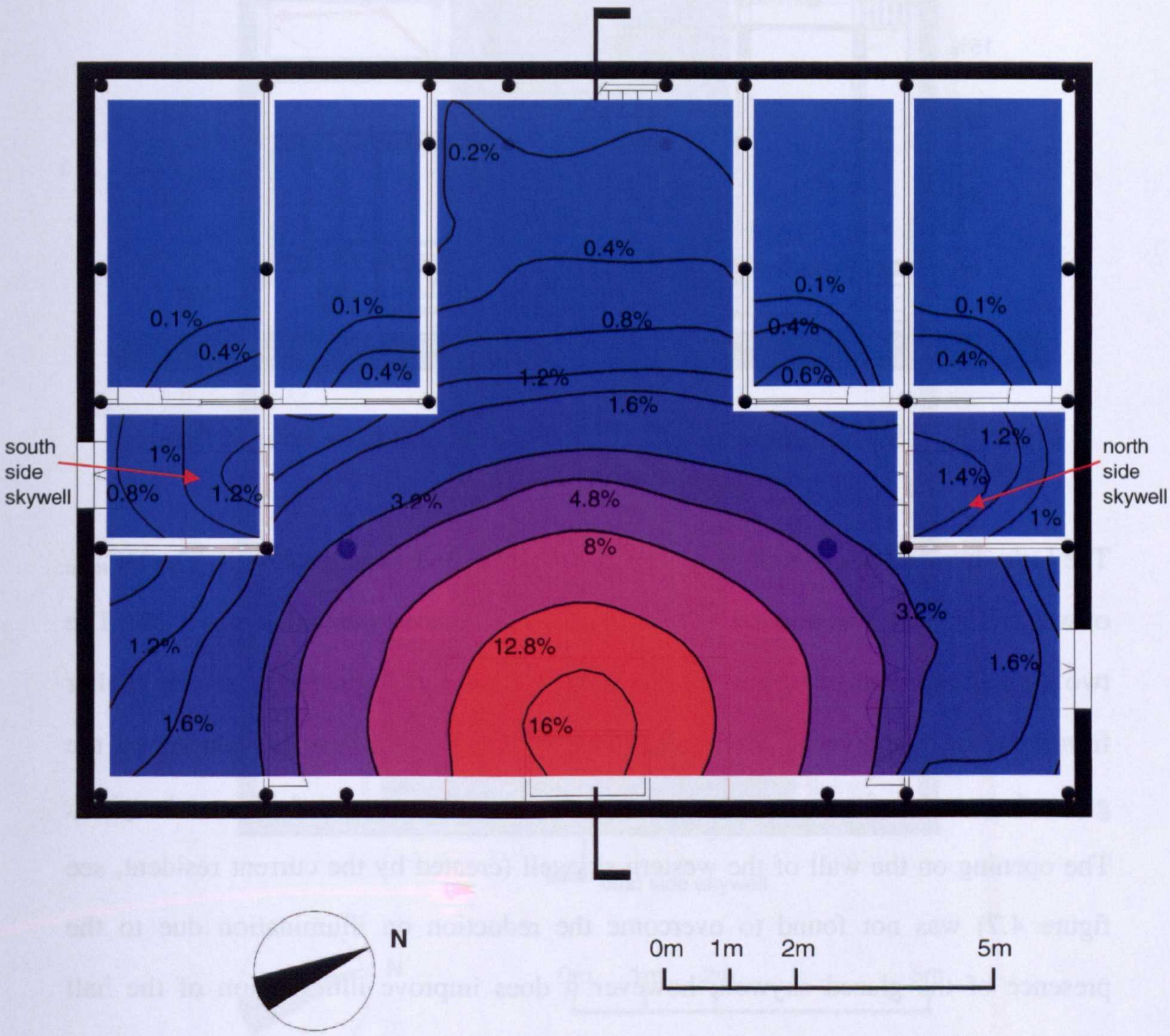


Figure 5. 10 DF isolux contour in ground floor level of Dunren dwelling

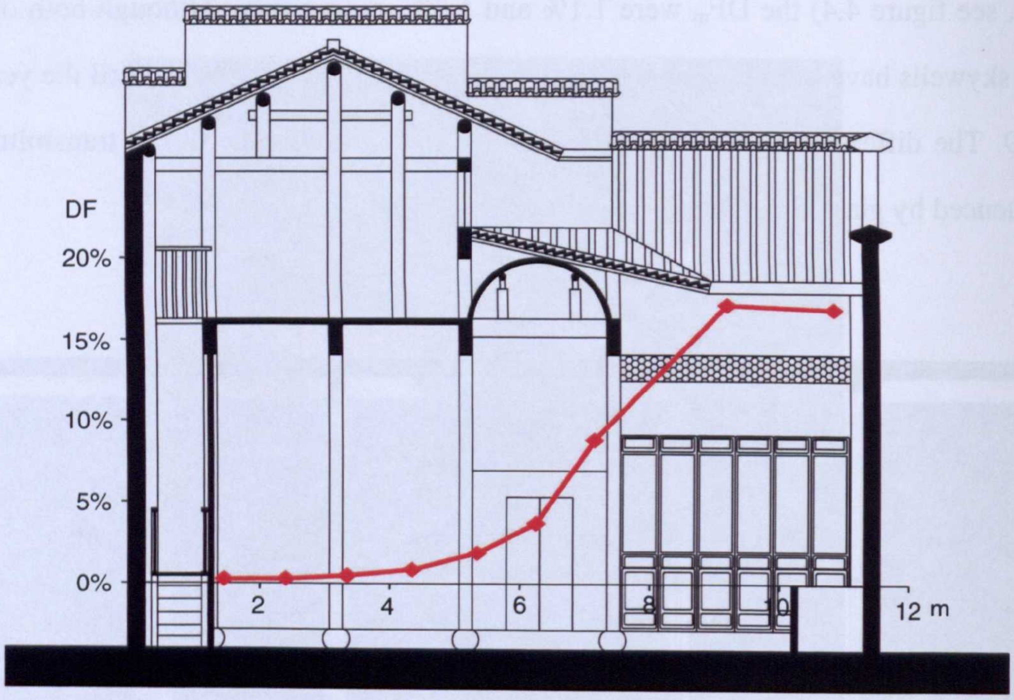


Figure 5. 11 Section showing DF at 1m above ground floor level of Dunren dwelling

The Lufu dwelling has two skywells: western skywell and eastern skywell. The $DF_{m,uti}$ of western skywell was about 1.4% while in skywell of east this value was 3.2%. The two skywells are similar in size, but the west side skywell is glazed to provide shelter from rain; in this skywell the transmittance of light is significantly reduced by the glass, the wooden frame supporting the glass and the accumulated dirt on the glass. The opening on the wall of the western skywell (created by the current resident, see figure 4.7) was not found to overcome the reduction on illumination due to the presence of the glazed skywell; however it does improve illumination of the hall adjacent to the western skywell (figure 5.12). The $DF_{m,hall}$ in west side and east side hall were very close (1.1% and 1.2% respectively), despite the better daylighting condition under the eastern skywell. This is because the opening provides side lighting and allows light to reach the back of the west side hall.

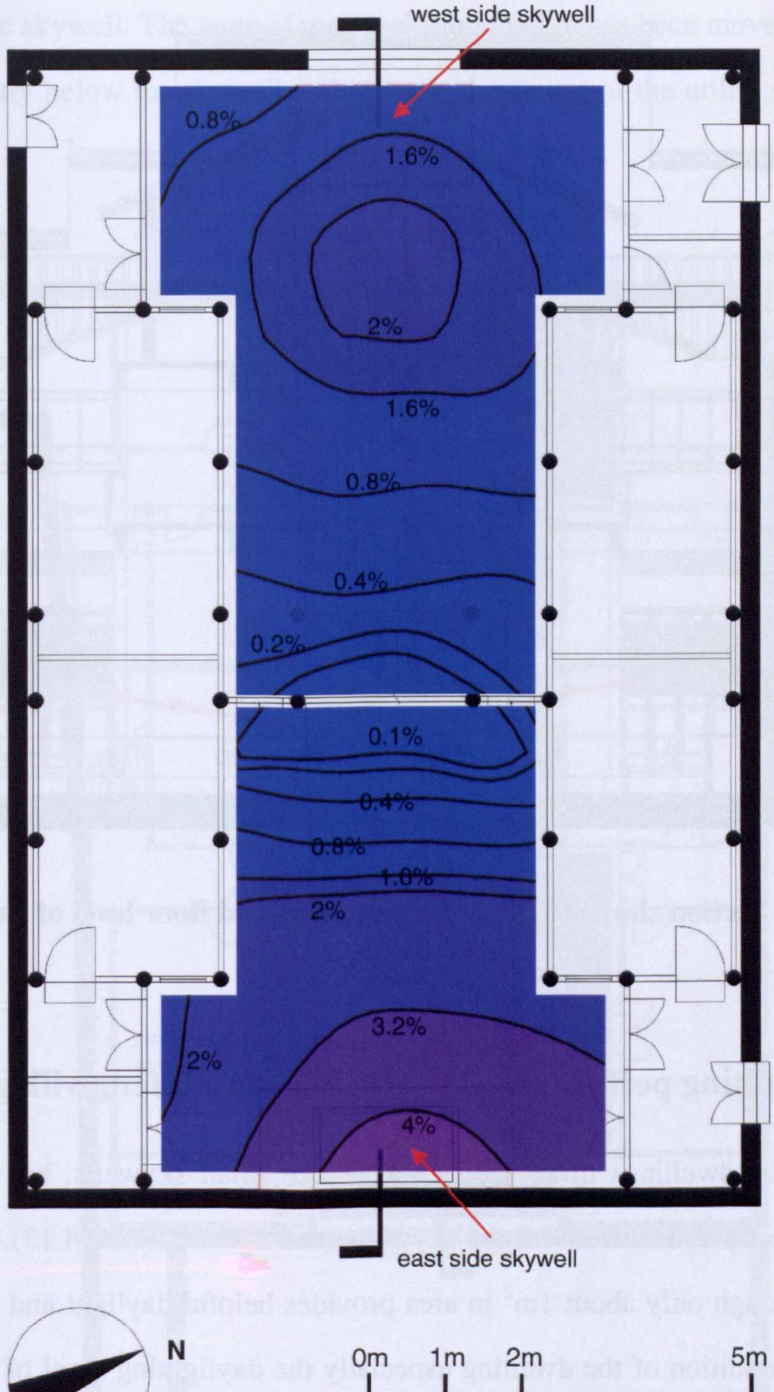


Figure 5. 12 DF isolux contours in ground floor level of Lufu dwelling

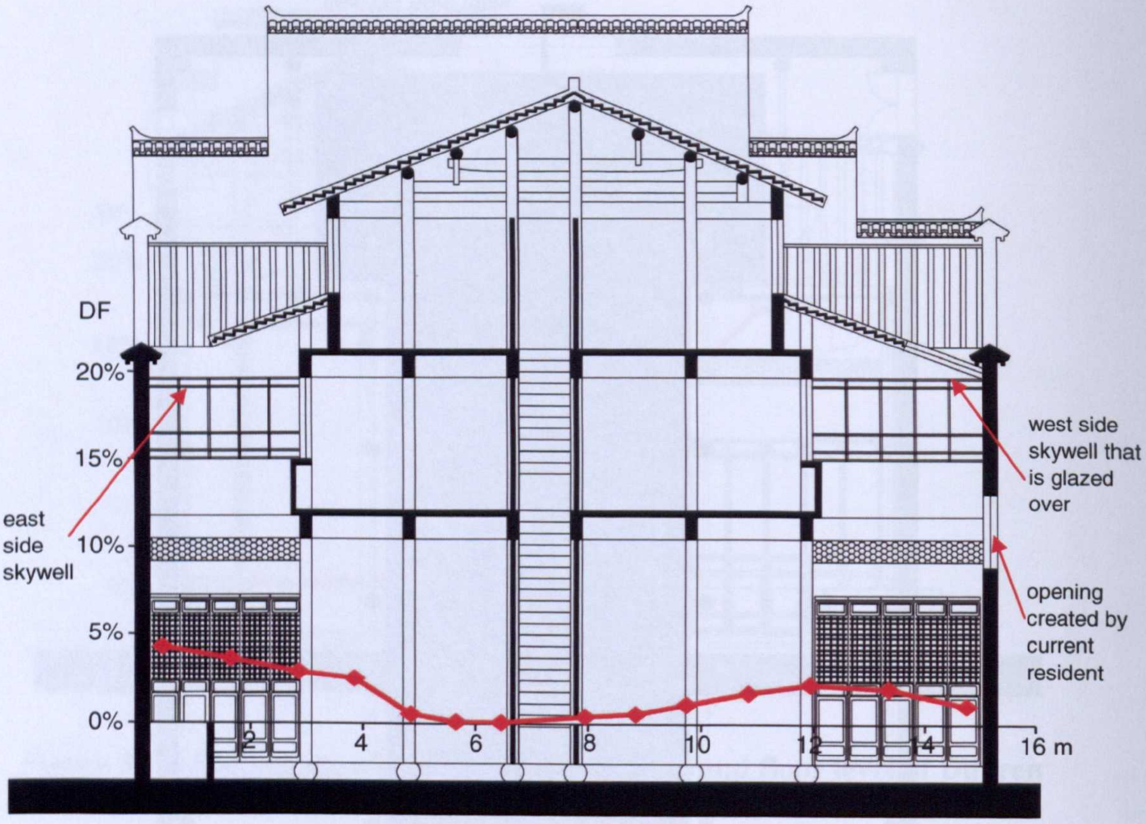


Figure 5. 13 Section showing DF at 1m above ground floor level of Lufu dwelling

5.4 Daylighting performance of dwellings in Zhifeng village

The vernacular dwellings in Zhifeng village have small skywells, but with vertical openings directly connected with the skywells (see figures 4.12 – 4.13). This vertical opening, although only about 1m^2 in area provides helpful daylight and improves the daylighting condition of the dwelling especially the daylighting level of the hall. The DF pattern on ground floor level in the Panxianxiong and the Panmaotai dwelling is described below.

In Panxianxiong dwelling, the $DF_{m,uti}$ and $DF_{m,hall}$ in the southern skywell was 1.2% and 0.7% while in the northern skywell these values were 1.8% and 1.2% respectively. Due to the small size of skywell, the daylighting level within this dwelling was poor. However, the vertical opening in the southern skywell does improve the daylighting level under the skywell. The zone of maximal illumination has been moved away from the area directly below the skywell and towards the centre of the utility space (figure 5.14).

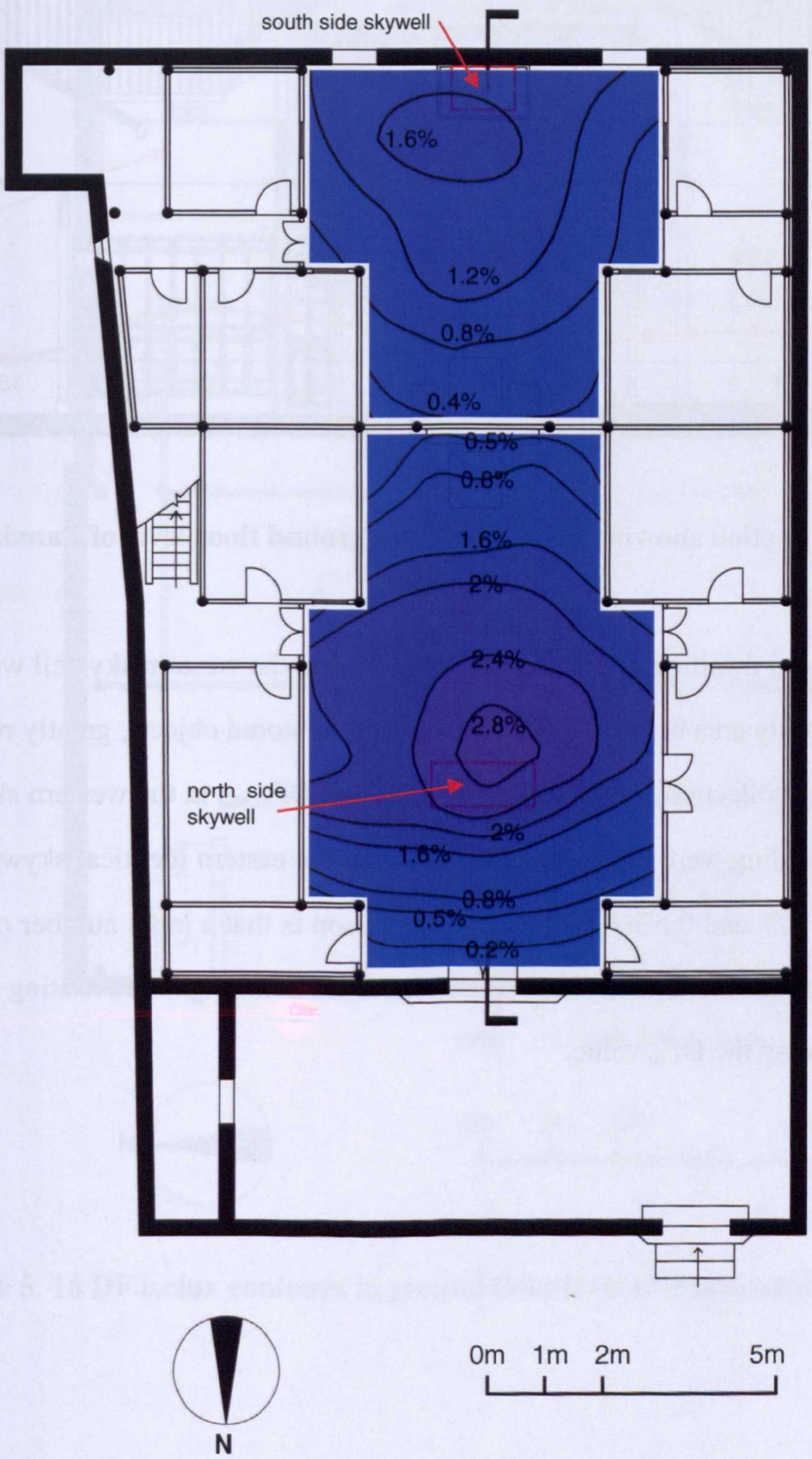


Figure 5. 14 DF isolux contours in ground floor level of Panxianxiong dwelling

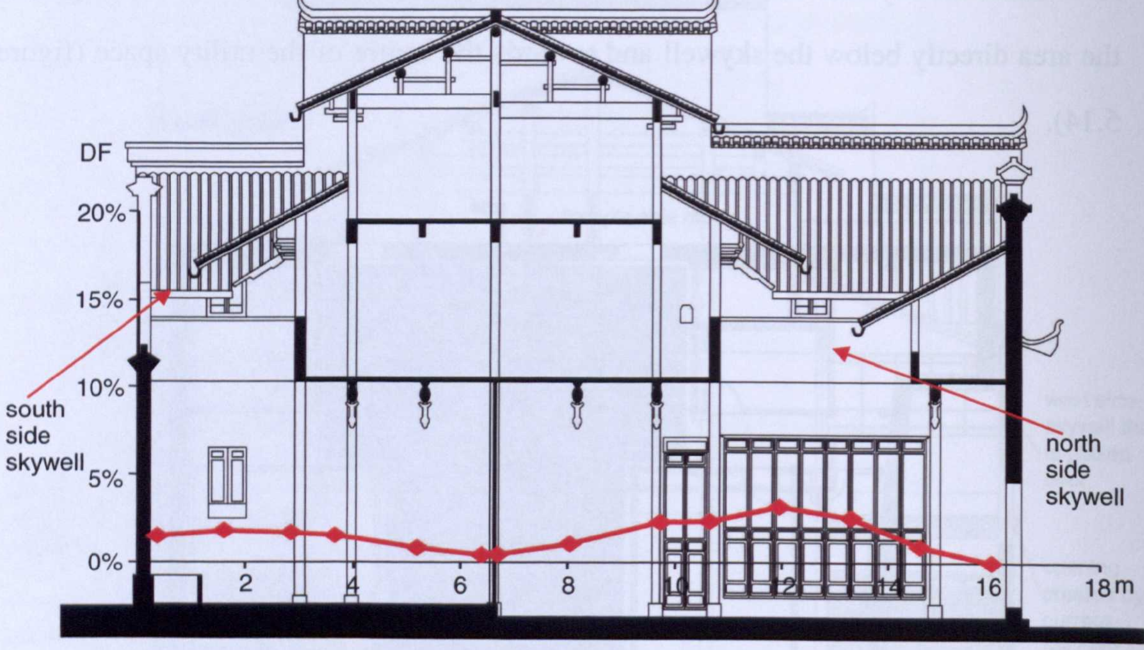


Figure 5. 15 Section showing DF at 1m above ground floor level of Panxianxiong dwelling

In the Panmaotai dwelling, the value of $DF_{m,util}$ within the western skywell was absent because the utility area below the skywell was full of stored objects, greatly restricting access for data collection. The values of $DF_{m,sky}$ and $DF_{m,hall}$ in the western skywell of Panmaotai dwelling were 0.8% and 0.4% while in the eastern identical skywell, these values were 1.2% and 0.5% respectively. The reason is that a large number of objects were stored in the western skywell. These absorbed some light penetrating from the skywell, reducing the DF_m value.

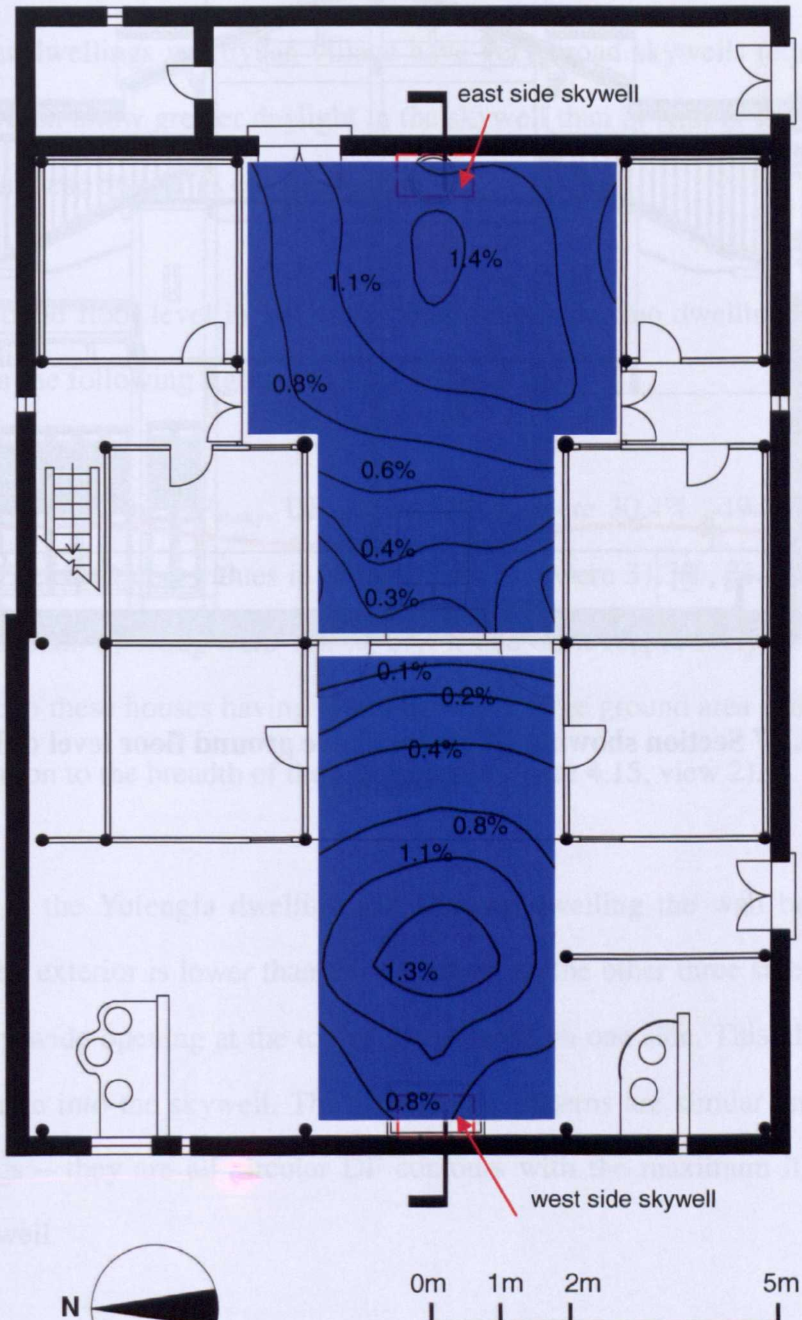


Figure 5. 16 DF isolux contours in ground floor level of Panmaotai dwelling

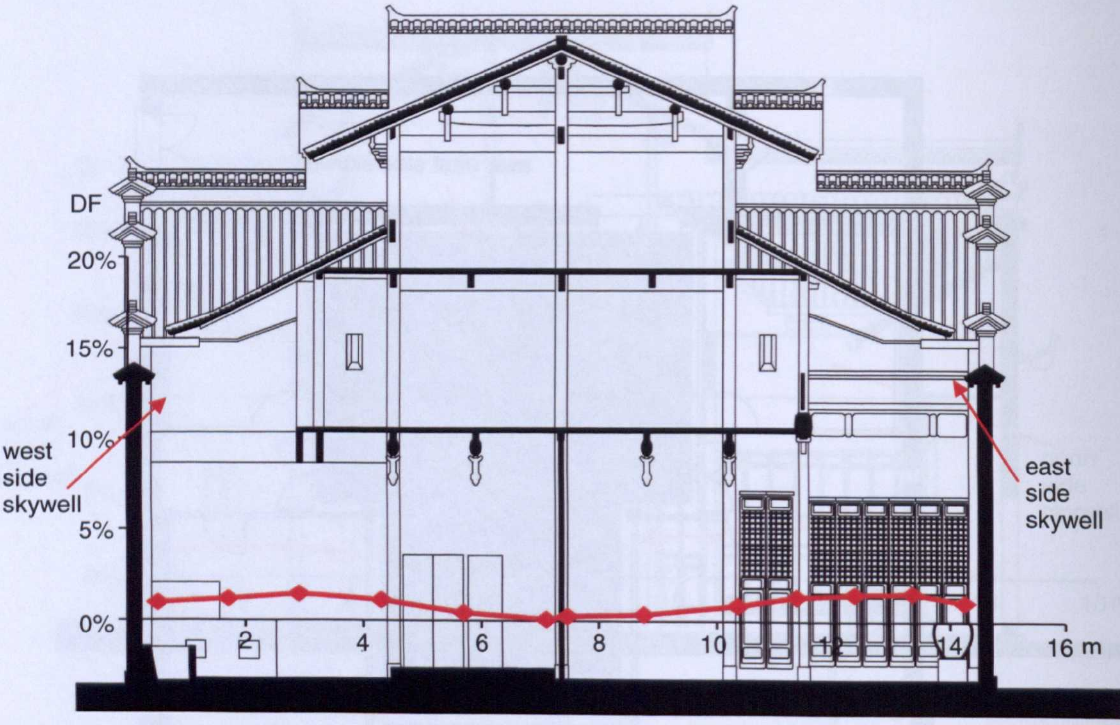


Figure 5. 17 Section showing DF at 1m above ground floor level of Panmaotai dwelling

5.5 Daylighting performance of dwellings in Yuyuan village

The vernacular dwellings in Yuyuan village have very broad skywells (equivalent as courtyards), which allow greater daylight in the skywell than in Xidi or Zhifeng. High level of DF_m in these dwellings can be examined.

The DF on ground floor level in Yufengfa, Shuting and Gaozuo dwellings have been summarized in the following figures (figures 5.18 – 5.23).

In Yufengfa dwelling, the $DF_{m,sky}$, $DF_{m,uti}$ and $DF_{m,hall}$ were 30.4% , 19.2% and 4.7% respectively. The equivalent values in Shuting dwelling were 31.3%, 21.5% and 3.6% and those in Gaozuo dwelling were 45.5%, 29.7% and 6.2% respectively. The high DF values are due to these houses having skywells with a large ground area and walls that are low in relation to the breadth of the skywell (see figure 4.15, view 2).

Furthermore, in the Yufengfa dwelling and Shuting dwelling the wall between the skywell and the exterior is lower than the structures on the other three sides, in effect creating a very wide opening at the top of the skywell on one side. This allows more light to penetrate into the skywell. The DF contour patterns are similar among these three dwellings – they are all circular DF contours with the maximum illumination under the skywell.

Although $DF_{m,hall}$ values of the studied dwellings were high, the daylighting is unevenly distributed. From the sections showing DF distribution at 1m above ground floor level of the dwellings, the DF was reduced sharply from the middle part of the skywell to the back of the hall.

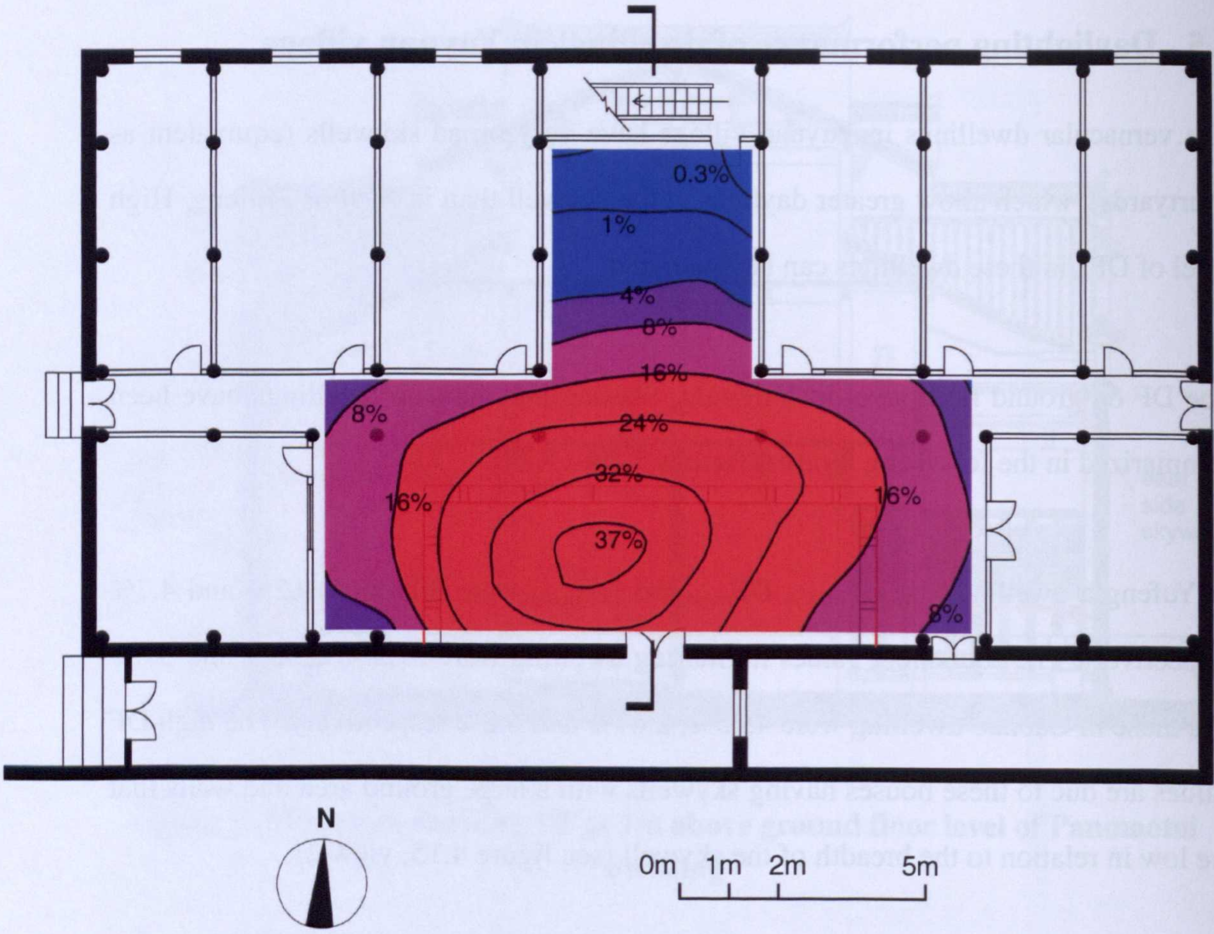


Figure 5. 18 DF isolux contour in ground floor level of Yufengfa dwelling

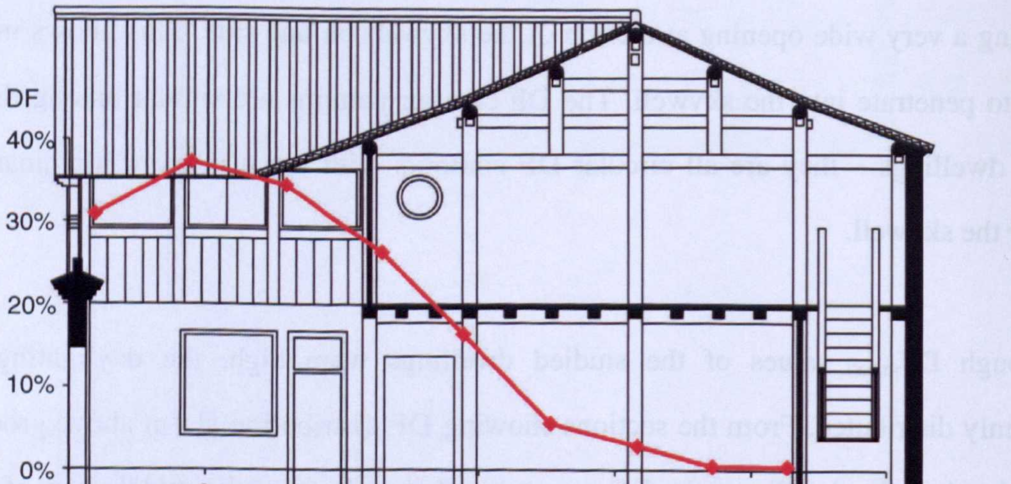


Figure 5. 19 Section showing DF at 1m above ground floor level of Yufengfa dwelling

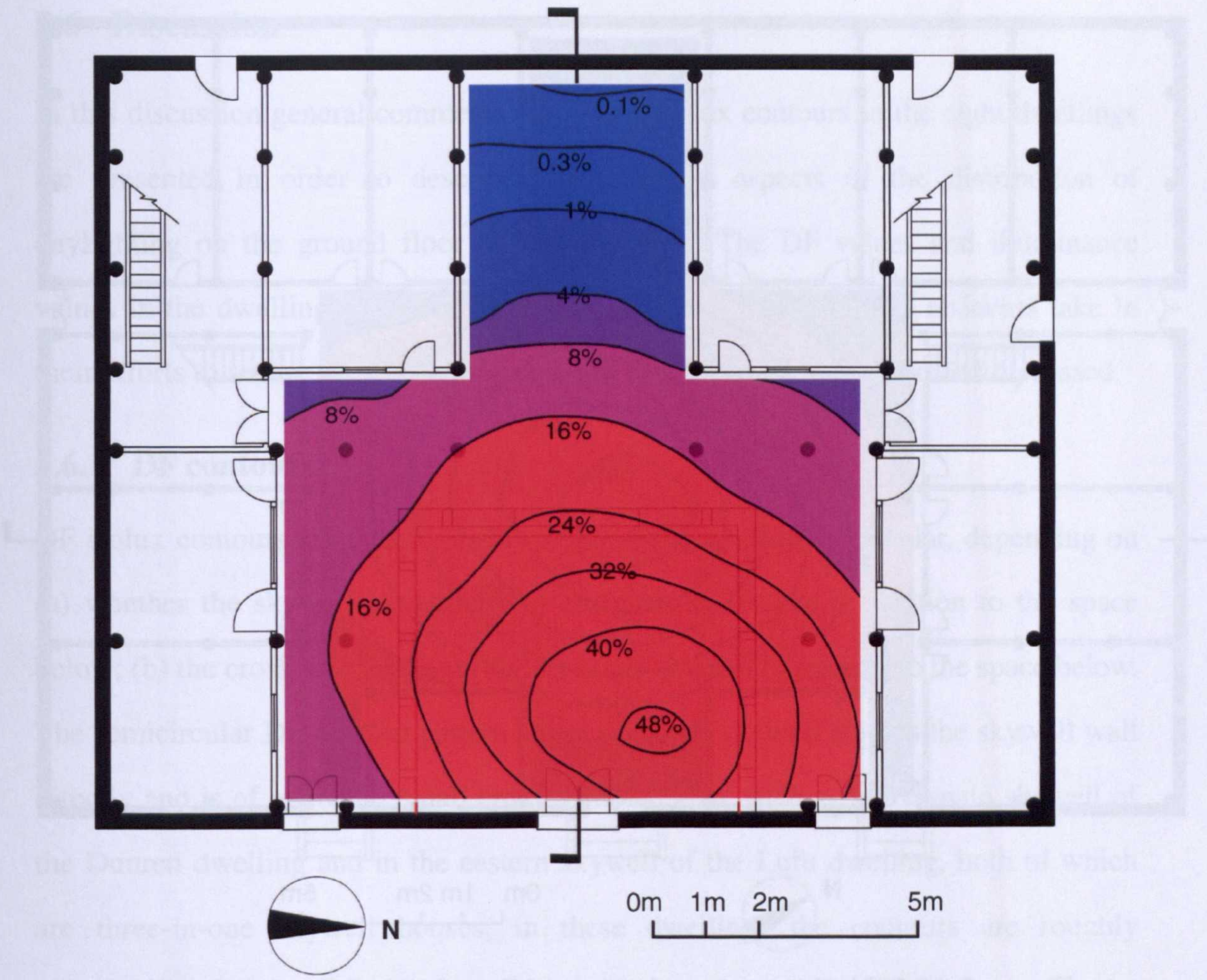


Figure 5. 20 DF isolux contour in ground floor level of Shuting dwelling

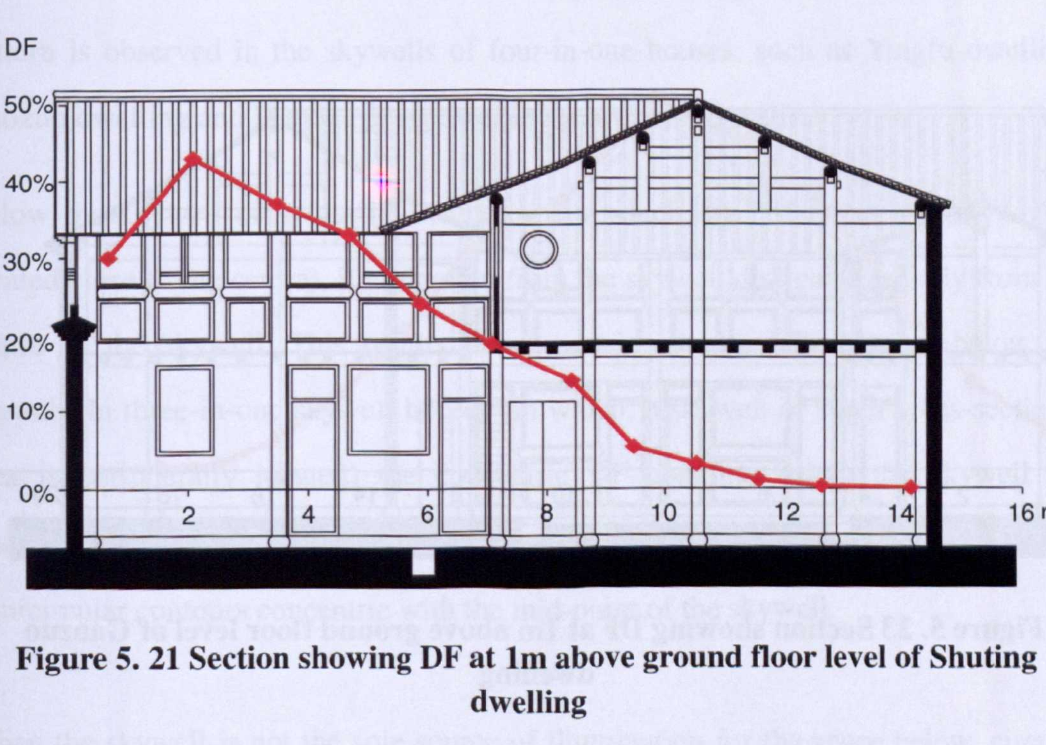


Figure 5. 21 Section showing DF at 1m above ground floor level of Shuting dwelling

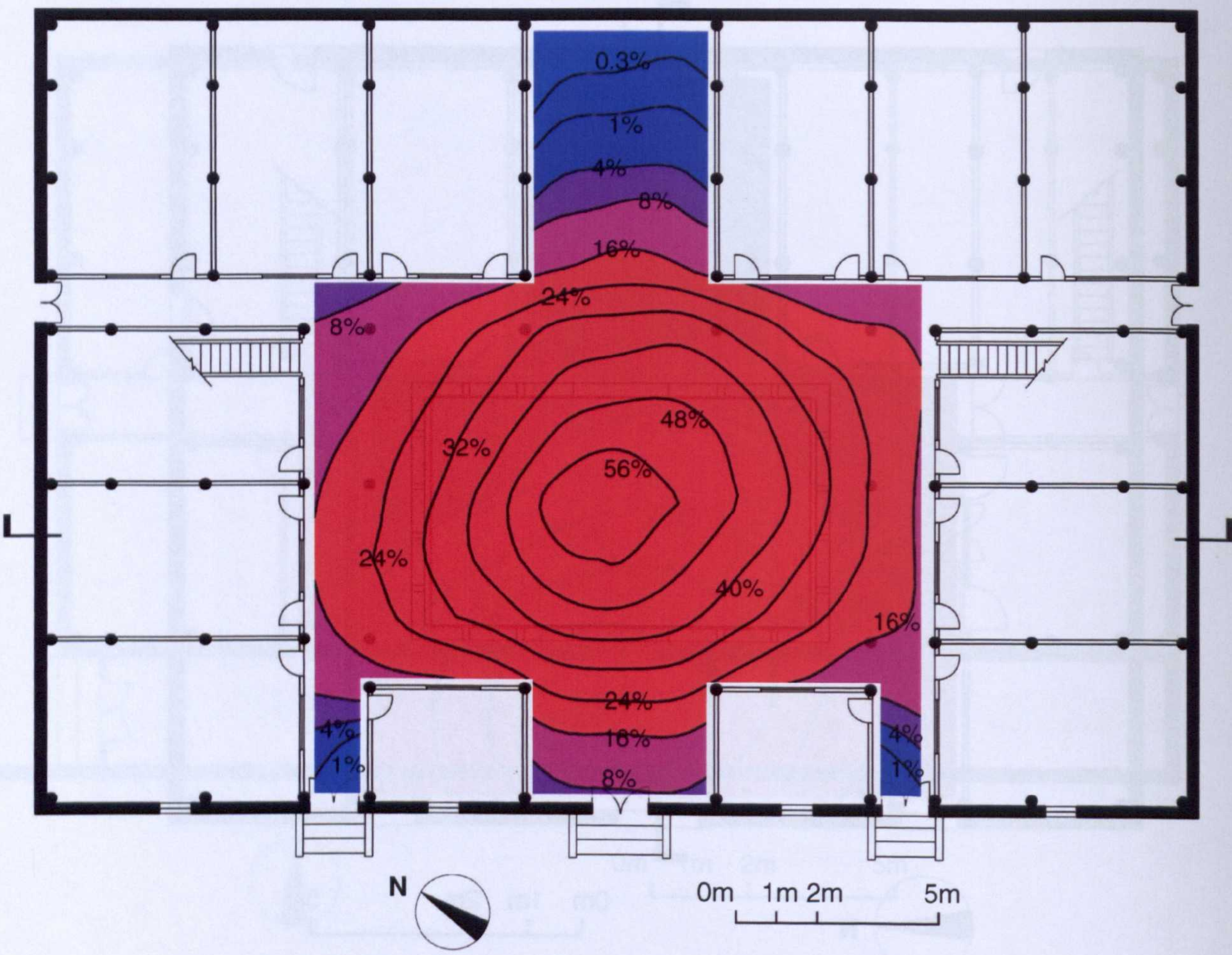


Figure 5. 22 DF isolux contour in ground floor level of Gaozuo dwelling

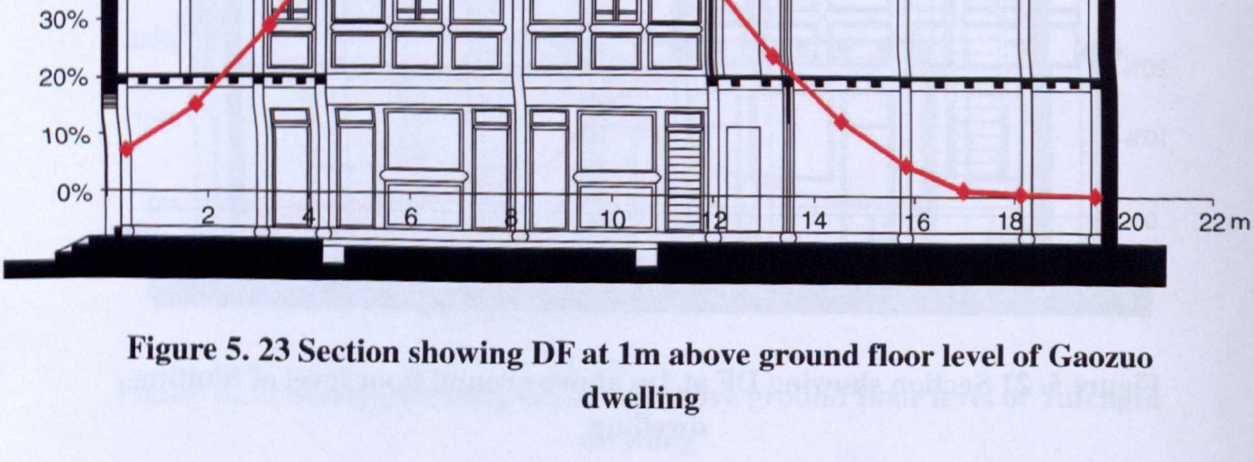


Figure 5. 23 Section showing DF at 1m above ground floor level of Gaozuo dwelling

5.6 Discussion

In this discussion general comments on the DF isolux contours in the eight dwellings are presented in order to describe some general aspects of the distribution of daylighting on the ground floor of the dwellings. The DF values and illuminance values in the dwellings are then discussed. Adaptive measures that residents take in their efforts to secure satisfactory daylighting conditions are described and discussed.

5.6.1 DF contours

DF isolux contours are either roughly semicircular or roughly circular, depending on (a) whether the skywell is centrally or peripherally located in relation to the space below; (b) the cross-sectional area (CSA) of the skywell in relation to the space below. The semicircular DF contour pattern arises when the skywell adjoins the skywell wall directly and is of relatively small cross-sectional area, such as in the main skywell of the Dunren dwelling and in the eastern skywell of the Lufu dwelling, both of which are three-in-one skywell houses; in these dwellings the contours are roughly concentric with the skywell's mid-point. In the circular DF contour pattern, the contours are also concentric around the mid-point of the skywell. The circular contour pattern is observed in the skywells of four-in-one houses, such as Yingfu dwelling, Gaozuo dwelling and Panxianxiong dwelling (northern skywell).

Below the skywell of a four-in-one house (in which, by definition, the skywell is located close to the centre), illumination from the skywell dissipates radially from the centre of the skywell. This results in concentric circular DF contours below the skywell. In three-in-one skywell houses (in which, a skywell of small cross-sectional area is peripherally located) the concentric DF contours below the skywell are bisected by the wall adjoining the skywell (skywell wall), giving rise to roughly semicircular contours concentric with the mid-point of the skywell.

When the skywell is not the sole source of illumination for the space below, circular

DF contour patterns which are concentric around the zone of maximal illumination, are also observed in the skywells of three-in-one houses. Examples of this pattern of illumination include the Lufu dwelling (western skywell), panmaotai dwelling (eastern and western skywell), Panxianxiong dwelling (southern skywell), Yufengfa dwelling and Shuting dwelling. Three types of opening in the wall between the skywell and the exterior were observed in the three-in-one dwellings studied.

- Small opening at top of wall between skywell and exterior – opening is contiguous with skywell. Found in Zhifeng village only. Examples: eastern and western skywell of Panmaotai dwelling and southern skywell of Panxianxiong dwelling.
- Wall between skywell and exterior is lower than the structures on the other three sides, in effect creating a very wide opening at the top of the skywell on one side. Found in Yuyuan village. Examples: Yufengfa dwelling and Shuting dwelling.
- Small opening in wall between skywell and exterior part way up the wall. Opening cut by present residents after construction of house. Sole example: western skywell of Lufu dwelling, Xidi village.

The semicircular pattern of illumination observed beneath a small peripheral skywell is due to the radial illumination beneath the skywell being bisected by the skywell wall. When an opening is present in that wall, the opening contributes some oblique illumination to the total illumination of the space. The oblique illumination from the opening displaces the semicircular illumination contours away from the skywell and gives rise to circular illumination contours towards the centre of the space.

In some three-in-one dwellings, the cross-sectional area of a skywell is large in relation to the area of the space below the skywell. In these dwellings the centre of the skywell – which is the centre of illumination – is towards the centre of the illuminated area. This means that the illumination contours are almost circular instead of bisecting the otherwise circular illumination contours, the skywell wall only cuts a small segment from the contours, giving largely circular illumination contours. The three-in-one houses in which this occurs – Yufengfa dwelling and Shuting dwelling – also have a skywell wall which is lower than the structure on the other three sides of the skywell. As noted above, the low wall is effectively a very wide vertical opening, which also contributes to the establishment of a circular illumination pattern by displacing the centre of illumination towards the centre of the skywell.

5.6.2 DF values and illuminance values

The values of WI, $DF_{m,\,sky}$, $DF_{m,\,uti}$ and $DF_{m,\,hall}$ of the eight dwellings studied in detail are summarized in table 5.3. Skywells were each assigned a designation W1, W2, W3 etc, with the integer value increasing with increasing W1. Skywells having identical WI were distinguished by additional letters (eg. W8a, W8b).

The relationships between WI and each of $DF_{m,\,sky}$, $DF_{m,\,uti}$ and $DF_{m,\,hall}$ are shown in figure 5.24. Data from W7, W8a and W8b are not presented in the figure because these skywells are all glazed. This affects their illumination properties and renders comparison of illumination data from these skywells with data from the other skywells invalid. W11b is not represented in the figure because the utility area beneath the western skywell of the Panmaotai dwelling was full of stored objects, greatly restricting access for data collection. The Dunren dwelling has three skywells (W4, W8a and W8b) above a single hall, so only a single value of $DF_{m,\,hall}$ is given. This value is given in relation to the largest skywell, W4, because as can be seen in figure 5.10 (contour diagram), the eastern skywell is the only one that influences the illumination of the hall. The values of $DF_{m,sky}$ and $DF_{m,uti}$ in W8a were 1.3% and 1.2%, and in W8b were 1.1% and 0.9% of the two identically constructed skywells. W8a had the higher DF_m values because the glass covering W8a was installed later than the glass above W8b; it was thus cleaner and had better transmittance than that in W8b.

Table 5. 3 Dimensions of skywells and ground floor DF data for the eight dwellings studied in detail

village	dwelling names and designations of skyells (in parentheses)		dimensions L x W x H (m)	WI	$DF_{m,sky}$	$DF_{m,uti}$	$DF_{m,hall}$
Yuyuan	Gaozuo dwelling (W1)		9.3X5.8X5	0.7	45.5%	29.7%	6.2%
	Shuting dwelling (W2)		6.1X5.2X5.3	0.94	31.3%	21.5%	3.6%
	Yufengfa dwelling (W3)		9.2X2.95X4.9	1.1	30.4%	19.2%	4.7%
Xidi	Dunren dwelling	eastern skywell (W4)	4.3X2.15X5.26	1.83	14.4%	6.2%	0.7%
		northern skywell (W8a)	1.2X1.45X7.6	5.6	1.3%	1.2%	nd
		southern skywell (W8b)	1.2X1.45X7.6	5.6	1.1%	0.9%	nd
	Yingfu dwelling (W5)		4.2X1.8X6.8	2.7	10.0%	7.4%	1.9%
	Lufu dwelling	eastern skywell (W6)	3.3X1.35X7.8	4.07	3.7%	3.2%	1.2%
		western skywell (W7)	2.3X1.3X7.5	4.67	1.3%	1.4%	1.1%
Zhifeng	Panxianxiong dwelling	northern skywell (W9)	1.8X0.75X6.3	5.95	2.5%	1.8%	1.2%
		southern skywell (W10)	1.1X0.75X6.2	6.95	1.5%	1.2%	0.7%
	Panmaotai dwelling	eastern skywell (W11a)	1.1X0.6X6	7.73	1.2%	1.0%	0.5%
		western skywell (W11b)	1.1X0.6X6	7.73	0.8%	nd	0.4%

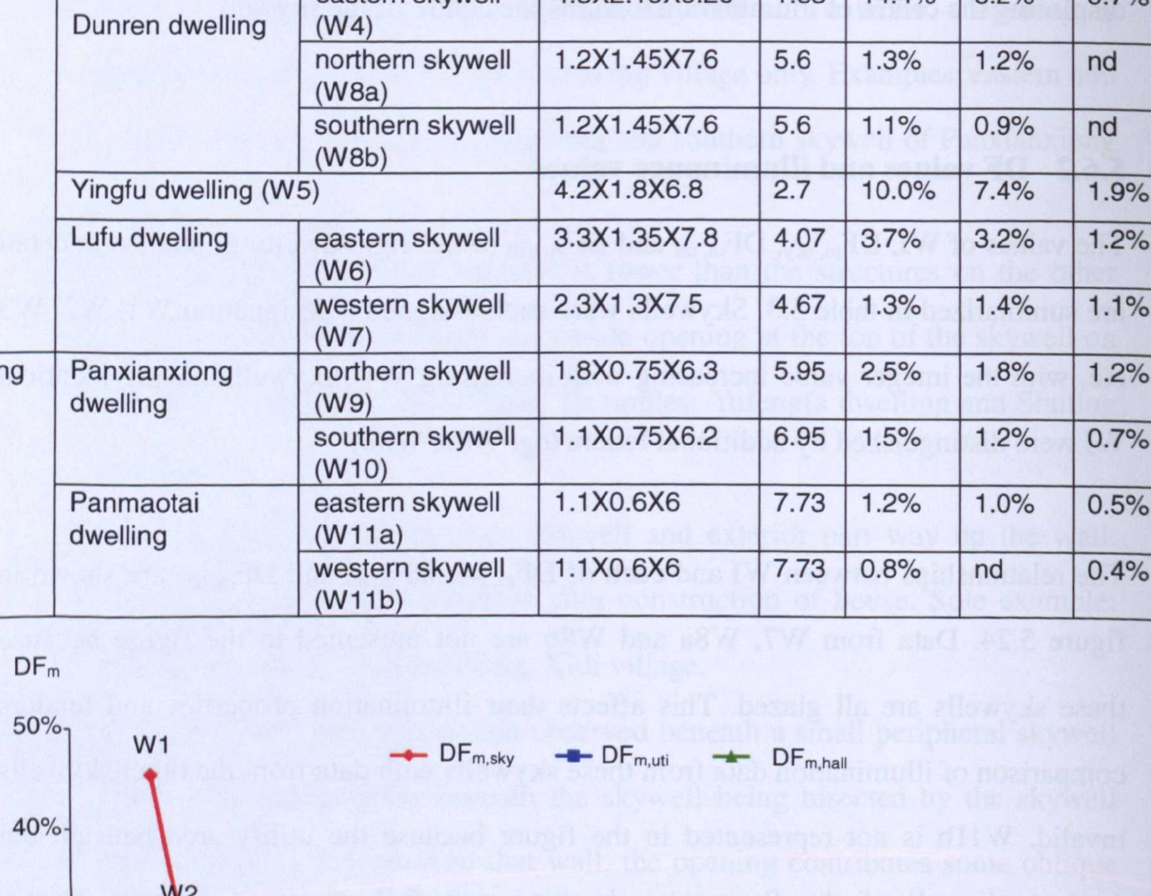


Figure 5. 24 The relationship between WI and $DF_{m,sky}$, $DF_{m,uti}$ and $DF_{m,hall}$

Considering the range of WI values derived from the measurement in the dwellings, WI rose from 0.7 to 7.73, the value of $DF_{m,sky}$ fell from 45.5% to 1.2%. A high WI represents a tall and narrow skywell, which gives a poor daylight level of the skywell. Dwellings in Yuyuan village have low WI (less than 1.1), and thus have abundant illuminance ($DF_{m,sky}$ values above 30%); while dwellings in Zhifeng village have high WI (larger than 5.9) thus give poor daylighting ($DF_{m,sky}$ values below 2.5%).

The trend in values of $DF_{m,uti}$ within the skywells followed that of $DF_{m,sky}$; this is as might be expected, since the main source of daylighting in the utility area is the skywell. Area of skywell as a proportion of area of utility area (skywell area fraction) is also an important determinant of $DF_{m,uti}$. The larger the value of $DF_{m,sky}$ (implying more light penetrating into the skywell) and the higher the skywell area fraction (for a given value of area of skywell, this means less area of utility area that need to be illuminated), the larger the value of $DF_{m,uti}$ will be (the better the daylighting in the utility area will be). As can be seen in table 5.4 below, dwellings in Yuyuan village have by far the largest values of skywell area fraction and the largest values of $DF_{m,sky}$; hence, they also have the largest values of $DF_{m,uti}$. Dwellings in Xidi village have intermediate values of $DF_{m,uti}$, and of $DF_{m,sky}$ and skywell area fraction. Dwellings in Zhifeng village have the lowest value of $DF_{m,uti}$, and of $DF_{m,sky}$ and skywell area fraction.

The $DF_{m,uti}$ value of W5 is slightly higher than that of W4 which is contrary to the general trend of DF_m falling with increasing WI. Since the two skywells have very similar values of skywell area fraction the main reason for the deviation from the trend is difference in skywell position. W5 is located centrally above a utility area, while W4 is located at the periphery of another utility area. It follows that the daylighting in the utility area containing W5 is more evenly distributed (UR = 0.39) than that containing W4 (UR = 0.11).

Table 5. 4 Area of skywell as percentage of area of utility area (area proportion) for eight of the skywells of the studied dwellings

village	dwelling/ skywell		area of skywell (m^2)	area of utility area (m^2)	area of skywell as percentage of area of utility area (area proportion)	$DF_{m,sky}$	$DF_{m,uti}$
Yuyuan	Gaozuo dwelling (W1)		53.94	159.1	33.90%	45.5%	**29.7%**
	Shuting dwelling (W2)		31.7	94.5	33.54%	31.3%	**21.5%**
	Yufengfa dwelling (W3)		27.1	77.6	34.92%	30.4%	**19.2%**
Xidi	Dunren dwelling	eastern skywell (W4)	9.245	58.2	15.88%	14.4%	**6.2%**
	Yingfu dwelling (W5)		7.56	49.6	15.24%	10.0%	**7.4%**
	Lufu dwelling	eastern skywell (W6)	4.455	17	26.21%	3.7%	**3.2%**
Zhifeng	Panxianxiong dwelling	northern skywell (W9)	1.35	32.8	4.12%	2.5%	**1.8%**
		southern skywell (W10)	0.825	22.7	3.63%	1.5%	**1.2%**
	Panmaotai dwelling	eastern skywell (W11a)	0.66	23.4	2.82%	1.2%	**1.0%**

The main contribution to $DF_{m,sky}$ is light which penetrates into the skywell directly; $DF_{m,uti}$ is determined both by the light penetrating into the skywell directly and light reflected by skywell surfaces (figure 5.25). However, $DF_{m,hall}$ is mainly determined by reflected light which originates from the daylight penetrating into the skywell since the hall area can only receive a small amount of light directly from the skywell. For a given skywell, $DF_{m,sky} > DF_{m,uti} > DF_{m,hall}$ (figure 5.24). All values of $DF_{m,hall}$ are very small – less than 2%, except for dwellings in Yuyuan village, which have $DF_{m,hall}$ values around 5% due to their large skywells.

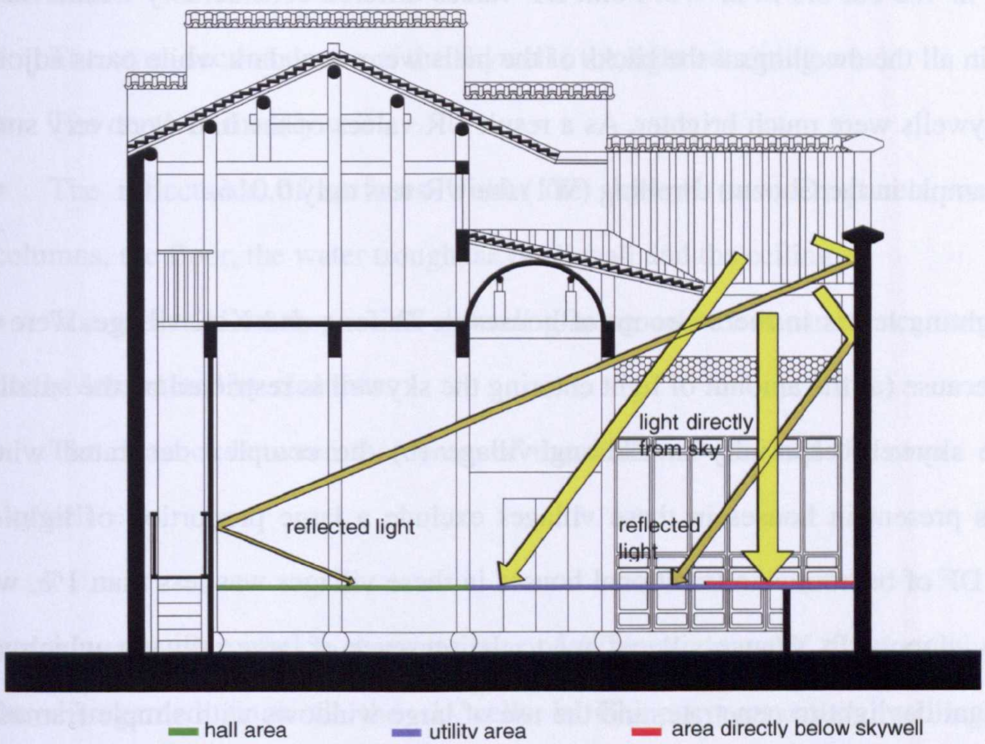


Figure 5. 25 Daylighting condition within a skywell house is influenced by the light direct from the sky and the reflected light

The value of $DF_{m,hall}$ depends on the quantity of light entering the skywell (the more light that enters the skywell, the more light can be reflected into the hall) and the mean distance between individual points in the hall and the skywell (i.e. distance between the centre of the hall and the centre of the skywell) in a given skywell house. This is because shorter the distance between the centre of the hall and that of the skywell, the more opportunity the hall has to receive light directly from the skywell, and the better its daylighting condition.

The $DF_{m,hall}$ value of W4 is slightly lower than that of W5, just as the $DF_{m,uti}$ value of W4 is slightly lower than that of W5 (see figure 5.24). This is due to the difference in distances between the centre of the skywell and the centre of the hall in the two buildings, as noted above. Distance between the centre of the hall and the centre of the skywell is 7 m in W4 but 6 m in W5. Similarly, the $DF_{m,hall}$ value of W2 is lower than that of W3 – distance between the centre of the hall and the centre of the skywell is

8.6 m in W2 but 6.6 m in W3. Point DF values differed considerably within the hall areas in all the dwellings – the backs of the halls were very dark while parts adjoining the skywells were much brighter. As a result UR values of the hall were very small – for example in the Gaozuo dwelling (W1) the UR was only 0.016.

Daylighting levels in the bedroom of houses in Zhifeng and Xidi village, were very low because (a) the amount of light entering the skywell is restricted by the small size of the skywell, especially in Zhifeng village (b) the complex decorated window frames present in houses in these villages exclude a large proportion of light. The mean DF of bedrooms in traditional houses in these villages was less than 1%, which is very gloomy. In Yuyuan village, due to the presence of large skywells which allow abundant daylight to penetrate, and the use of large windows with simple frames, the daylighting condition within bedrooms was much better. In the Yufengfa dwelling, residents have created a large bedroom window in an external wall of the building in order to add to the light supplied by the skywell. This has been done in the modern era.

In summary, dwellings in Yuyuan village have bright daylighting due to their large skywells – the mean of $DF_{m,sky}$, $DF_{m,uti}$ and $DF_{m,hall}$ of the three Yuyuan dwellings studied in detail were 35.7%, 23.5% and 4.8% respectively. Dwellings in Xidi village have medium sized skywell and good daylighting in the skywell and utility area but poor daylighting in the hall – the mean of $DF_{m,sky}$, $DF_{m,uti}$ and $DF_{m,hall}$ of the three Xidi dwellings studied in detail were 9.4%, 5.6% and 1.3% respectively. Dwellings in Zhifeng village have a very poor daylighting condtion due to the tiny skywell - the mean of $DF_{m,sky}$, $DF_{m,uti}$ and $DF_{m,hall}$ of the two Zhifeng dwellings studied were 1.7%, 1.3% and 0.8% respectively.

The daylighting level within a skywell dwelling is determined by the following considerations:

- The cross-sectional area of the skywell (the light admitting area)
- The depth of the skywell
- The reflectance of surfaces within the skywell (wooden panels, wooden columns, the floor, the water trough, skywell wall and the ceiling)
- The presence or absence of skywell glazing and its transmittance, which is partly determined by cleanness
- The distance between the centre of the observed area and the centre of the skywell

In comparing the illumination characteristics of different skywells, the skywell shape can be disregarded since all the skywells in Chinese vernacular dwellings are rectangular. The influence of glazing and its transmittance upon daylighting level is exemplified by the difference in $DF_{m,sky}$ between the eastern unglazed skywell and the western glazed skywell of the Lufu dwelling. Despite the additional light from an opening in the skywell wall in the western glazed skywell of the Lufu dwelling, $DF_{m,sky}$ of the western glazed skywell was lower than that of the eastern unglazed skywell (1.3% vs 3.7%).

When light enters the skywell (especially when the skywell is narrow and tall), it is the reflectance characteristics of the internal surfaces of the skywell space that dictate how daylight illuminance is distributed, and how much daylight can reach the floor level. Since the materials used in different skywell houses are similar (see 5.3), in comparing the daylighting conditions in two such houses the observed differences can be attributed to size and depth of the skywell and the distance between the centre of the observed area and the centre of the skywell.

The level of illumination at a given point in a skywell is the sum of light from the sky which illuminates that point directly and the amount of light reflected (a) from surfaces inside the skywell and (b) into the skywell from outside.

Light directly from the sky makes a larger contribution than reflected light to illumination within the skywell for the following reasons.

- The intensity of light is reduced at each reflection because of partial absorption by surface materials. In luminance testing in the present study, the reflectances of skywell surfaces (which were all diffuse, matt surfaces) were found to be low, ranging between 0.13 and 0.56. Differences were due to differences in surface materials.
- Since the opening of the skywell is much higher than the level at which illuminance was measured (roughly 1m above floor level), there are no objects above the skywell to reflect light directly into the lower part of the skywell area. When a skywell wall is present it can reflect a small amount of shallow angle incident light through the skywell and into the back of the adjoining hall – but the contribution of this pathway to total illumination is likely to be small, due to the small fraction of celestial illumination that is incident at a suitable angle, and the weak reflectance at the top of the skywell wall and the back wall of the hall. Reflection from adjoining tall buildings into the skywell can be disregarded as the traditional dwellings studied were surrounded by buildings of similar height. Within the skywell, light may be reflected many times until reaching the observed area; this reduces the intensity of illumination considerably.

Only a small amount of light directly from the sky can reach the hall (figure 5.25), so the reflected light may contribute a higher proportion of total illumination than in the skywell.

Within the eight skywell dwellings studied, it can be assumed that under the overcast sky condition the daylighting contour characteristics and the daylighting level at the foot of the skywell and in the utility area is mainly determined by the light directly from the sky vault.

In an ideal overcast sky condition, peak luminance is at the top of the sky vault. Luminance at the zenith is three times that at the horizon and decreases gradually from zenith to horizon (Szokolay, 2008).

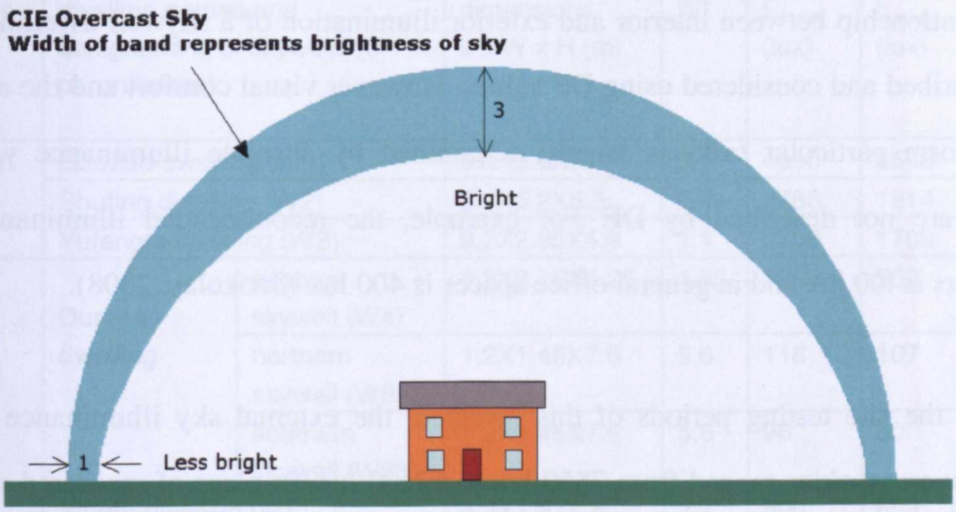


Figure 5. 26 CIE Overcast Sky (Source: Szokolay, 2008)

The larger the range of angles through which light can reach a point close to a skywell floor, the more light can reach that point and the stronger the illumination will be at that point. This range is widest at the centre of the skywell, since admittance of light to the skywell floor is constrained by the geometry of the skywell. At the centre of the skywell daylight shines upon the skywell floor almost vertically. Near-zenith light is more intense than light from shallow angles. This is a further reason for daylighting being strongest at the centre of a skywell.

The following propositions can be proved mathematically (see appendix G).

Proposition 1 When no source of illumination other than the opening of the skywell is present, the area immediately beneath a skywell is most strongly illuminated ($DF_{m,sky}$

has the highest value). Peak illuminance is at the mid-point of the skywell.

Proposition 2 For a skywell house, $DF_{m,uti}$ will be higher when the skywell is located centrally above the utility area than when it is located at the periphery of the utility area.

Proposition 3 When a high side opening is present in a room co-illuminated by a skywell, the point of maximal illumination will be close to the window.

The relationship between interior and exterior illumination of a skywell dwelling can be described and considered using DF values. However visual comfort and the ability to perform particular tasks is largely determined by absolute illuminance values, which are not described by DF. For example, the recommended illuminance in corridors is 100 lux and in general office spaces is 400 lux (Szokolay, 2008).

During the site testing periods of this research, the external sky illuminance level under overcast skies ranged from 7550 lux to 13600 lux. In place of measured values of sky illuminance a single value was calculated from village latitude using online software. Using the design sky illuminance calculator (http://wiki.naturalfrequency.com/wiki/Design_Sky), the design sky illuminance of the three villages studied was calculated to be 8900 lux; since they have very similar latitudes, the same value was used for all three villages. The value of 8900 lux was used to convert the values of $DF_{m,\ sky}$, $DF_{m,\ uti}$ and $DF_{m,\ hall}$ derived from on-site measurements into $E_{m,\ sky}$, $E_{m,\ uti}$ and $E_{m,\ hall}$ respectively.

Design sky illuminance values are derived from a statistical analysis of dynamic outdoor sky illuminance levels. By definition, design sky value is exceeded 85% of the time between the hours of 9:00 and 17:00 throughout the year. Therefore, the actual illuminance values within the skywell dwellings would exceed the values presented in table 5.5 85% of the time throughout the year.

Table 5. 5 Dimensions of skywells and ground floor illuminance data for the eight dwellings studied in detail

village	dwelling names and designations of skywells (in parentheses)		dimensions L x W x H (m)	WI	$E_{m,sky}$ (lux)	$E_{m,uti}$ (lux)	$E_{m,hall}$ (lux)
Yuyuan	Gaozuo dwelling (W1)		9.3X5.8X5	0.7	4050	2643	552
	Shuting dwelling (W2)		6.1X5.2X5.3	0.94	2786	1914	320
	Yufengfa dwelling (W3)		9.2X2.95X4.9	1.1	2706	1709	418
Xidi	Dunren dwelling	eastern skywell (W4)	4.3X2.15X5.26	1.83	1282	552	62
		northern skywell (W8a)	1.2X1.45X7.6	5.6	116	107	nd
		southern skywell (W8b)	1.2X1.45X7.6	5.6	98	80	nd
	Yingfu dwelling (W5)		4.2X1.8X6.8	2.7	890	659	169
	Lufu dwelling	eastern skywell (W6)	3.3X1.35X7.8	4.07	329	285	107
		western skywell (W7)	2.3X1.3X7.5	4.67	116	125	98
Zhifeng	Panxianxiong dwelling	northern skywell (W9)	1.8X0.75X6.3	5.95	223	160	107
		southern skywell (W10)	1.1X0.75X6.2	6.95	134	107	62
	Panmaotai dwelling	eastern skywell (W11a)	1.1X0.6X6	7.73	107	89	45
		western skywell (W11b)	1.1X0.6X6	7.73	71	nd	36

5.6.3 Adaptive measures to secure better daylighting

Measured illuminance values were found to correlate with the mean satisfaction with the natural illumination of their dwellings expressed by residents of traditional houses in the three villages. In Yuyuan village, where the large skywells give high levels of illumination, interviewees were very satisfied with the daylighting performance (satisfaction score 4.5). In Xidi village, skywell have a moderate cross-sectional area and respondents found the daylighting performance of their houses acceptable (mean satisfaction score 3.6), Zhifeng village skywells are small in cross-sectional area and residents reported low satisfaction with the poor daylighting they received (mean satisfaction score 2.6). Residents of Zhifeng village appear to be able to tolerate the very poor daylighting conditions in their houses since their mean satisfaction score was close to the neutral value 3. Residents of Xidi village gave a mildly positive score of 3.6 despite the poor daylighting in the halls and the gloomy bedrooms. This can be explained as follows:

1) In interviews most interviewees reported that they regarded bedrooms as sleeping areas that were only to be occupied during the night. When something needs to be done in the bedroom during the daytime, the residents will turn on the light temporarily.

2) Different visual tasks require different illuminance. For example 100 lux may be far less than the illuminance that is needed for writing but may be sufficient for moving through a corridor. Common visual tasks within Chinese vernacular skywell dwellings and their illuminance requirements are summarized in table 5.6.

Table 5. 6 Illuminance for visual tasks commonly undertaken in Chinese vernacular skywell dwellings (adapted from Szokolay, 2008)

visual task		illuminance
casual viewing	corridor	100 lux
	stairs	100 lux
	chatting *	100 lux *
rough task, large detail	casual reading	200 lux
	kitchen	200 lux
	dining room	200 lux
	playing cards	200 lux
ordinary task, medium detail	shop	400 lux
	writing *	400 lux *
fairly severe task, small detail	goods displaying *	750 lux *

* no data in Szokolay (2008); present author's estimate based on illuminance requirements for comparable tasks given in Szokolay (2008)

3) Although the recommended illuminance level for casual reading is 200 lux and that for reading is 400 lux, it was possible to read a newspaper at only 30 lux at the back of the hall in the Lufu dwelling during the testing period.

4) Residents of vernacular dwellings often take actions to obtain their preferred daylighting conditions.

In Xidi village, residents tend to move themselves and any objects they are using in pursuance of a task in order to obtain satisfaction in daylighting.

Figure 5. 27 Reading (casual and sustained) in the Dunren dwelling (Xidi village)

The lady (left) who sells souvenirs from the Dunren dwelling has placed a desk under the skywell for relaxing and reading in better lighting conditions than in the shop (a side room) when there is no trade (figure 5.27). The other lady (right) is shown standing to read a book for a short time at the edge of the utility area rather than sit within the hall area where the illuminance level is low.

Figure 5. 28 A desk in the Lufu dwelling (Xidi village) placed close to the skywell to ensure good daylighting for reading and writing

Residents of Lufu dwelling did not use the original desk located in the main hall for reading or writing but placed another desk near the skywell to obtain better lighting conditions for these activities (figure 5.28).

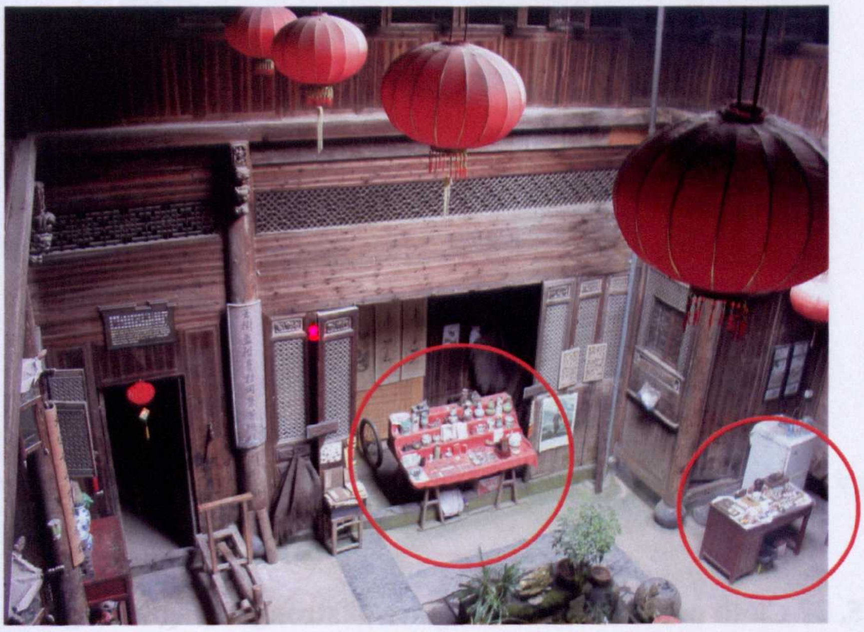


Figure 5. 29 Goods in the Yingfu dwelling (Xidi village) displayed outside the shop but around the skywell, so as to obtain better illumination

In the Yingfu dwelling, goods are displayed outside the shop but around the skywell to obtain high level of illumination (figure 5.29). In the shop within the Dunren dwelling the light is turned on occasionally to allow shoppers to see the goods in detail.

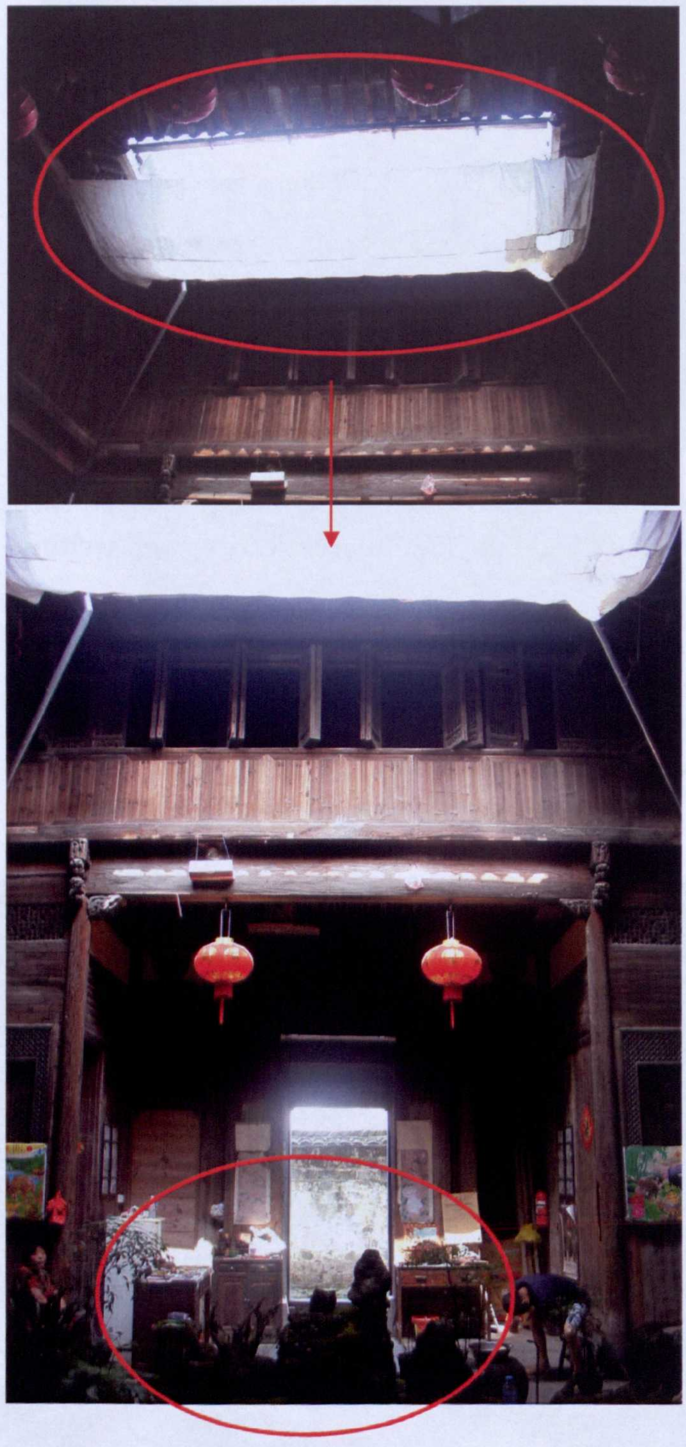


Figure 5. 30 Cloth used to reduce the glare of strong sunlight on goods in the Yingfu dwelling

The owner of the shop within the Yingfu dwelling use a piece of cloth to cover the skywell and thus to reduce the glare due to strong direct illumination by the skywell. The cloth attenuates and diffuses the strong incident light (figure 5.30).

In Zhifeng village, residents rarely spend much time in the skywell or the hall due to the low illuminance level; they generally prefer to be in the yard where illumination is sufficient. When the external illumination is strong, residents stay within the skywell but keep the door open. The extent of opening of the door is adjusted by the residents (figure 5.31).

Figure 5. 31 Residents of the Panmaotai dwelling open the door to varying extents to control lighting conditions inside the skywell

In Yuyuan village, residents tend to avoid excessive daylight since the illuminance level tends to be high even on overcast days.

Figure 5. 32 Residents of Gaozuo dwelling (Yuyuan village) shown relaxing and playing cards under the veranda to avoid excessive sunlight in a summer day.

In figure 5.32, it is likely that the residents of the Gaozuo dwelling in Yuyuan village benefit from the lower illuminance level rather than thermal shading. This is because they have not chosen to locate themselves in the hall, which is fully shaded but has a lower illuminance level than the veranda.

Different lighting conditions within a Chinese vernacular dwelling can change the mood of occupants. According to Baker and Steemers (2000), daylighting has an important role in expressing the architectural intentions of the building, and may also affect the pleasure and well-being of the occupants. In fact the residents enjoy the sunlight not only because winter sunlight can warm people but also because the moving of the sunlight within the skywell has a subtle impact on the residents' feelings (figure 5.33 and 5.34).

Figure 5. 33 The change of illumination by sunlight in skywell of Dunren dwelling (Xidi village) in a summer day

Figure 5. 34 The change of illumination by sunlight in Dunren skywell (Xidi village) in a winter day

5.7 Conculsion

Two patterns of DF isolux contour in skywell dwellings were identified. Below the skywell of a four-in-one house, illumination from the skywell dissipates radially from the centre of the skywell. This results in concentric circular DF contours below the skywell. In three-in-one skywell houses (in which a skywell of small cross-sectional area is peripherally located) the concentric DF contours below the skywell are bisected by the wall adjoining the skywell (the skywell wall), giving rise to roughly semicircular contours concentric with the mid-point of the skywell.

Dwellings in Yuyuan village have a bright daylit appearance due to their broad skywells – mean values of $DF_{m,sky}$, $DF_{m,uti}$ and $DF_{m,hall}$ were 35.7%, 23.5% and 4.8% respectively. Dwellings in Xidi village have good daylighting in the skywell and utility area but poor daylighting condition in the hall – mean values of $DF_{m,sky}$, $DF_{m,uti}$ and $DF_{m,hall}$ were 9.4%, 5.6% and 1.3%. Dwellings in Zhifeng village have a very poor daylighting condition due to their small skywells – mean values of $DF_{m,sky}$, $DF_{m,uti}$ and $DF_{m,hall}$ was 1.7%, 1.3% and 0.8% respectively. Daylighting levels in the bedrooms of houses in Zhifeng and Xidi villages, were very low because (a) the amount of light entering the skywell is restricted by the small size of the skywell, especially in Zhifeng village, and (b) the complex decorated window frames present in houses in these villages exclude a large proportion of light. The mean DF of bedrooms of traditional houses in Zhifeng and Xidi villages was less than 1%, which is very gloomy. In Yuyuan village, due to the presence of large skywells which allow abundant daylight to penetrate, and the use of large windows with simple frames, the daylighting condition within bedrooms was much better (the mean DF was more than 2%).

Measured illuminance values were found to correlate with the mean satisfaction with the natural illumination of their dwellings expressed by residents of traditional houses in the three villages. In Yuyuan village, where the large skywells give high levels of illumination, interviewees were very satisfied with the daylighting performance (satisfaction score 4.5). In Xidi village, skywell have a moderate cross-sectional area and respondents found the daylighting performance of their houses acceptable (mean satisfaction score 3.6), Zhifeng village skywells are small in cross-sectional area and residents reported low satisfaction with the poor daylighting they received (mean satisfaction score 2.6). Residents of Zhifeng village appear to be able to tolerate the very poor daylighting conditions in their houses since their mean satisfaction score was close to the neutral value 3. Residents of Xidi village gave a mildly positive score of 3.6 despite the poor daylighting in the halls and the gloomy bedrooms.

Historically, bedrooms in Chinese homes were regarded as sleeping areas which were only occupied during the night, so abundant illumination of these spaces was not considered a necessity. In the daytime, residents have always spent most of their time in the hall and the skywell, which together have been used as living spaces.

The residents of all three villages tend to take actions to pursue satisfactory daylighting conditions. In Xidi village, residents tend to move themselves and any objects they are using in pursuance of a task in order to obtain better daylighting condition; in Zhifeng village, residents spend less time in the skywell or the hall due to the low illuminance level in their house; they generally prefer to be in the yard where illumination is sufficient. When external illumination is strong, residents tend to stay within the skywell but keep the house doors open. The extent of opening of the doors is adjusted by the residents. In Yuyuan village, residents prefer to stay under the veranda or in the bedrooms to avoid excessive daylight since the illuminance levels tend to be high even on overcast days.

6 THERMAL PERFORMANCE

6.1 Introduction

The aim of the work described in this chapter is to answer research questions 4 'How comfortable are the residents of these vernacular dwellings in respect of temperature, illumination and humidity?' and 5 'How good is the environmental performance of skywell dwellings, as assessed by rigorous quantitative analysis of daylighting and thermal performance in summer and winter?' in respect of thermal performance. The method used to obtain measurements of DBT, RH, air velocity and surface temperature, and to simulate the direct solar radiation into the skywell void and the effect of mutual shading are given first. The results obtained using the questionnaire with respect to the residents' satisfaction on thermal performance in Chinese vernacular dwellings and the thermal data for the eight skywell dwellings obtained in the study are described and analyzed. The thermal environment of the skywell is discussed in detail with respect to several heat inputs and outputs – radiative heat gain/loss, conductive heat gain/loss, convective heat gain/loss, evaporative heat loss, and heat gain from internal sources.

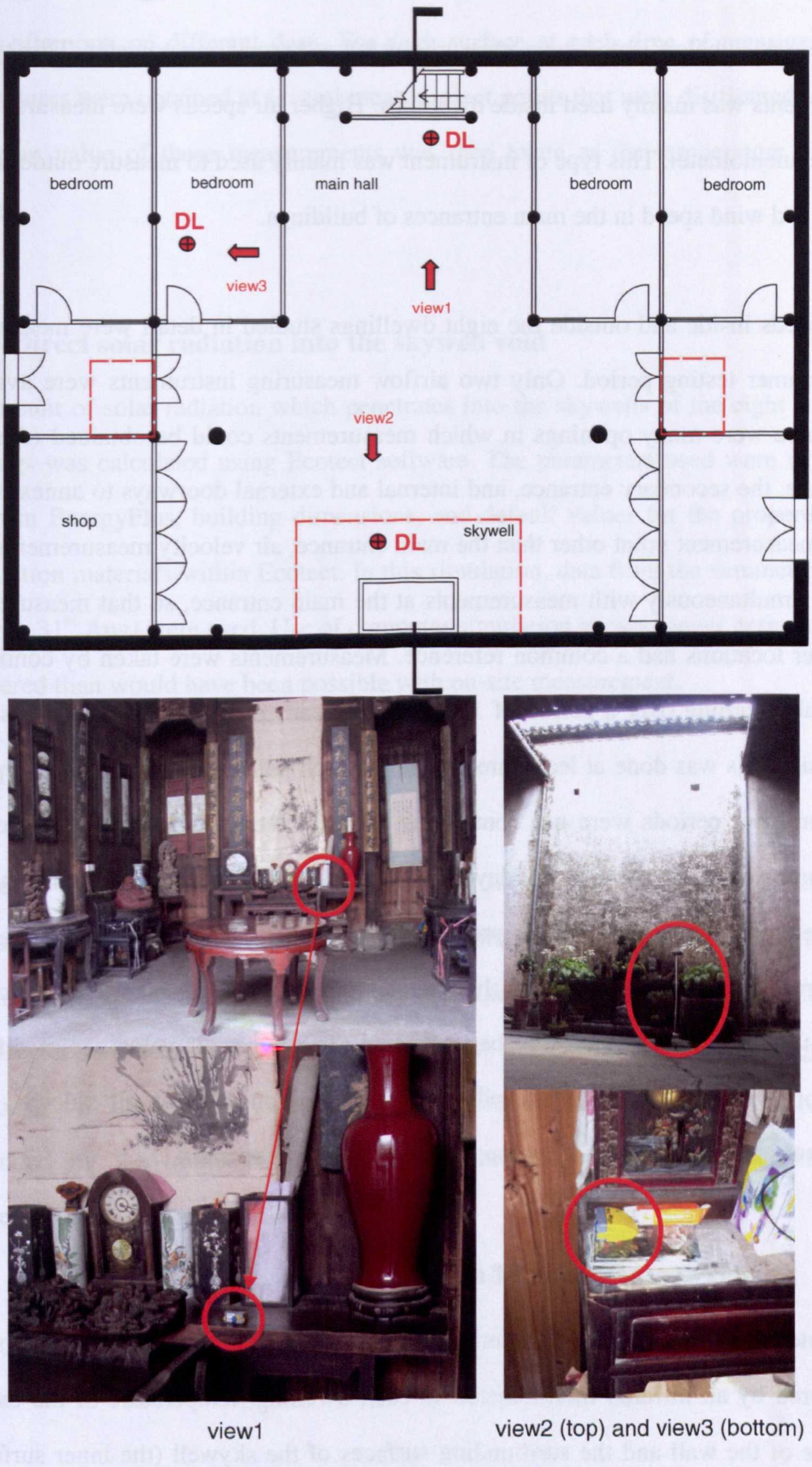
6.2 Method

6.2.1 Air temperature and relative humidity

Air temperature and humidity within the dwellings were recorded using data loggers (Gemini Data Loggers, UK). Data loggers which had been set to record the dry bulb air temperature (DBT) and relative humidity (RH) every minute were placed in the skywell, the hall and a bedroom of each house. Data loggers were placed at an approximate height of 1.5 m. For comparison in each village the DBT of air outside the dwellings was measured by placing a data logger on a flat roof of a contemporary building near the studied vernacular dwellings, to record the microclimate of the village. Data collected by this reference data logger was then compared with that collected within the dwellings. Data loggers located in skywells and rooftop were protected from sunlight and rain, while those placed inside the buildings were placed on items of furniture.

DBT and RH were recorded continuously over seven days in summer in the eight houses studied in detail. Equivalent data were collected for the eight houses in the three villages in winter but only data for the houses in Xidi and Yuyuan are presented; data for the houses in Zhifeng were obtained later in Feburary than data from the other two villages, and were distinctly higher. As a result, winter data from Zhifeng were judged not to be comparable to winter data from Xidi and Yuyuan. In this study, external air temperature or external DBT indicates the temperature recorded on the roof, which is the external temperature used for compassion against internal temperature. The data were exported to Excel through the software of Tinytag Explorer 4.7 (Gemini Data Loggers, UK). A summary of the data is given in section 6.3

The position of the data logger (DL) within a specimen studied dwelling (the Dunren dwelling) is shown in figure 6.1. Position of the data logger in the other vernacular dwellings is shown in appendix H.



view1

view2 (top) and view3 (bottom)

Figure 6. 1 Positions of data loggers in Dunren dwelling

6.2.2 Air velocity

Air velocities below $2ms^{-1}$ were measured using a thermal anemometer. This type of instruments was mainly used inside dwellings. Higher air speeds were measured using a vane anemometer. This type of instrument was mainly used to measure outdoor wind speed and wind speed in the main entrances of buildings.

Air speeds inside and outside the eight dwellings studied in detail were measured in the summer testing period. Only two airflow measuring instruments were available and there were many openings in which measurements could be obtained (the main entrance, the secondary entrance, and internal and external doorways to annexes). For each measurement point other than the main entrance, air velocity measurements were taken simultaneously with measurements at the main entrance, so that measurements at other locations had a common reference. Measurements were taken by continuous manual recording over a period of 10 minutes; means of these values were used for analysis. This was done at least three times for each pair of measurements. Replicate measurement periods were not contiguous. Unless otherwise stated, all air velocity measurements were made in the daytime. Mean air speeds at locations other than the main entrance were expressed as proportions of the air speed at the main entrance at that time, to enable non-concurrently obtained measurements of air speed at locations other than the main entrance to be compared. The mean air velocities at different locations in each of the eight dwellings as a proportion of mean air velocity in the main entrance measured at the same time are shown in appendix D.

6.2.3 Surface temperatures of dwellings

The internal and external surface temperatures of the eight vernacular dwellings were measured by an infrared thermometer. In each dwelling, temperature of the external surface of the wall and the surrounding surfaces of the skywell (the inner surface of the skywell wall, the surface of the skywell floor, the inner surface of the roof and the wooden panel lining) were measured at least three different times a day from morning to late afternoon on different days. For each surface at each time of measurement, temperatures were obtained at several measurement points that were distributed evenly. The mean value of these measurements was then taken as the temperature of that surface.

6.2.4 Direct solar radiation into the skywell void

The amount of solar radiation which penetrates into the skywells of the eight studied dwellings was calculated using Ecotect software. The parameters used were weather data from EnergyPlus, building dimensions, and default values for the properties of construction materials within Ecotect. In this simulation, data from the summer period (1^{st} Jun – 31^{st} Aug) were used. Use of computer simulation allows longer periods to be considered than would have been possible with on-site measurement.

6.2.5 Effect of mutual shading

In order to evaluate the effect of mutual shading in summer, the Yingfu dwelling in Xidi village was taken as an example. Indirect solar gain (the heat obtained through solar radiation incident on opaque surfaces) of the Yingfu dwelling was simulated using Ecotect software and climate data of Tunxi weather station from EnergyPlus. The house was modelled in Ecotect both as an isolated building and as a structure surrounded by the immediately neighbouring buildings present in Xidi village. Parameters used were as described in 6.2.4 above.

6.3 Results and discussion

In questionnaires, residents of the three villages reported that they could maintain thermal comfort in summer with the opening of doors and only infrequent recourse to the use of fans. The mean scores for satisfaction with thermal comfort in summer in Xidi, Zhifeng and Yuyuan villages were 4.4, 4.0 and 3.4 respectively. The corresponding scores in winter in the houses were 2.0 in Xidi, 2.2 in Zhifeng, and 2.7 in Yuyuan, thus people generally felt cold but not severely so. Residents of Zhifeng and Xidi felt very humid in their houses in summer and returned unfavourable mean satisfaction scores of 2.3 and 2.6. In Yuyuan village, the mean satisfaction score was a marginally favourable 3.1.

In each village the DBT and RH data inside and outside the skywells of vernacular dwellings studied are shown in figures 6.2 – 6.6. During the summer measuring period, the ambient air of the three villages was hot and humid. The minimum external DBTs were all over 21°C, and the maximum and mean external DBTs was 39.5°C and 27.6°C in Xidi, 41.6°C and 29.6°C in Zhifeng and 39.2°C and 27.6°C in Yuyuan. Most of the time, the RH was over 60% in the three villages. In the winter testing period, the ambient air of Xidi and Yuyuan village was very cold but not very humid. The minimal and mean external DBTs were -7.0°C and 1.7°C in Xidi, and -6.7°C and 3.5°C in Yuyuan.

For each village, on each of the study days maximal external DBT was observed around 14:00 and minimal external DBT around 05:00 in summer and 08:00 in winter in the early morning before the sun rose. The external DBT and RH fluctuated considerably; the mean external diurnal swings in Xidi, Zhifeng and Yuyuan villages in summer were calculated to be 12.5°C, 15.4°C and 11.8°C. In the winter testing period, the mean diurnal swings were 11.8°C in Xidi and 18.7°C in Yuyuan.

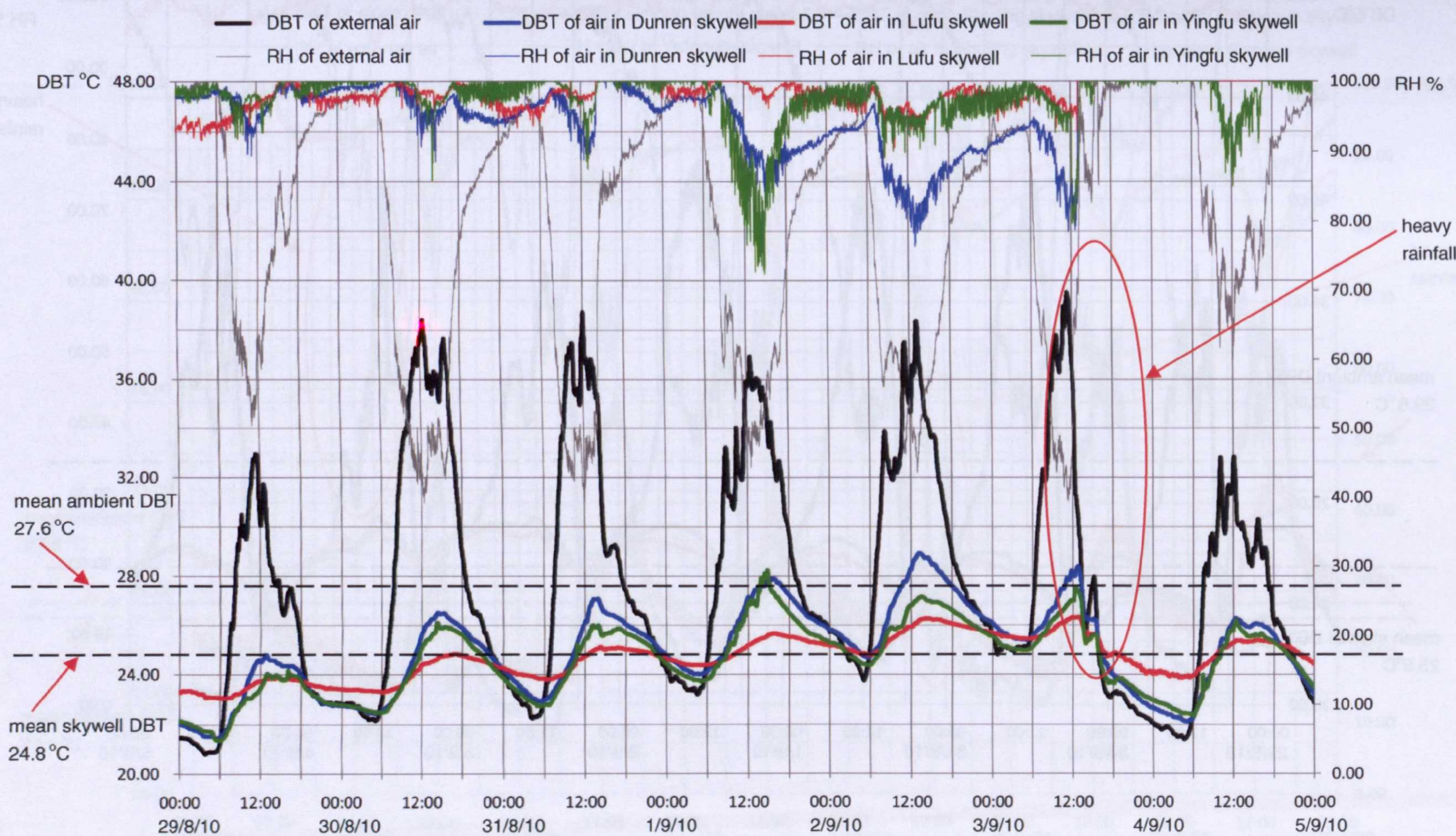


Figure 6. 2 Temperature and relative humidity data for dwellings in Xidi village in summer recording period

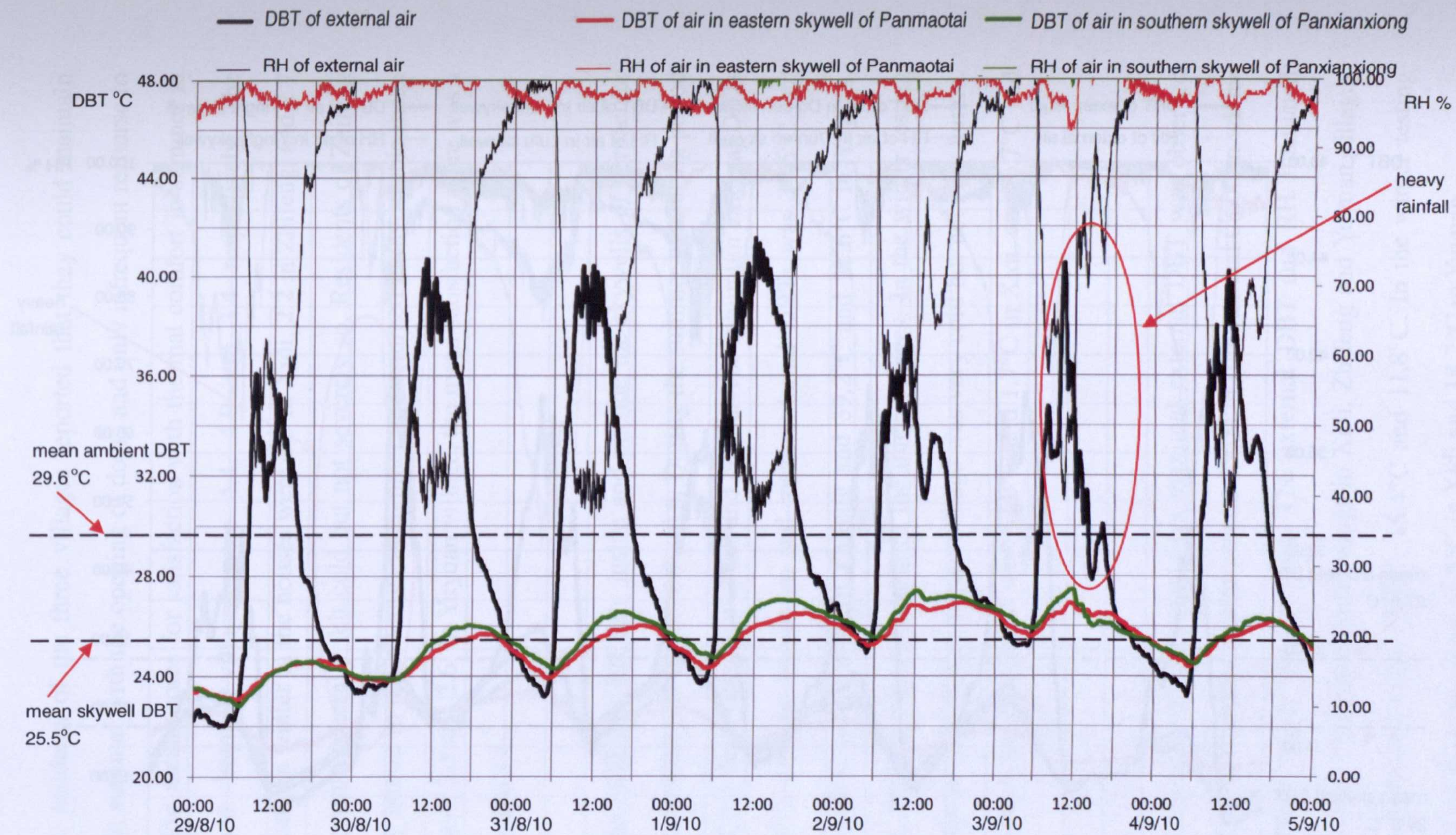


Figure 6. 3 Temperature and relative humidity data for dwellings in Zhifeng village in summer recording period

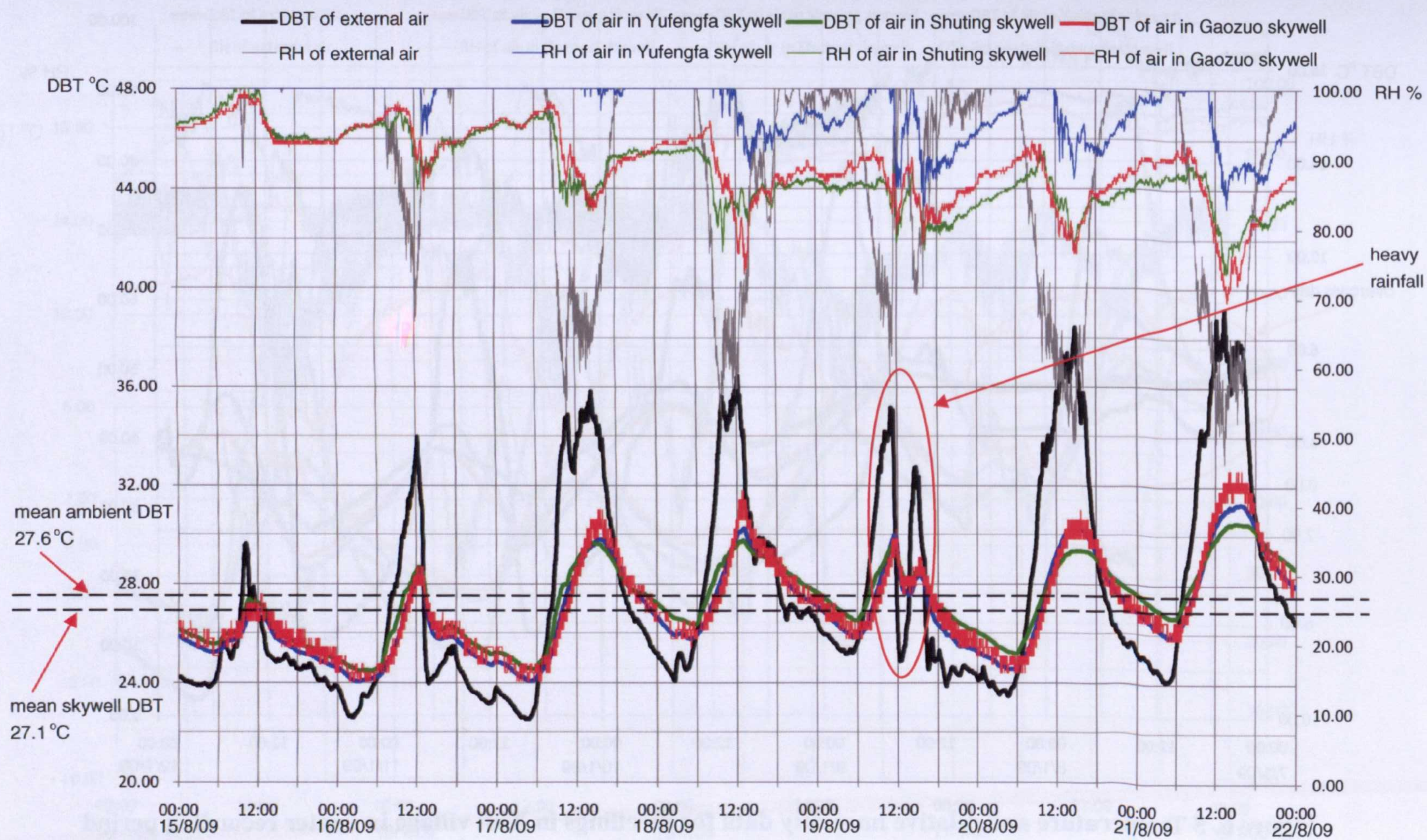


Figure 6. 4 Temperature and relative humidity data for dwellings in Yuyuan village in summer recording period

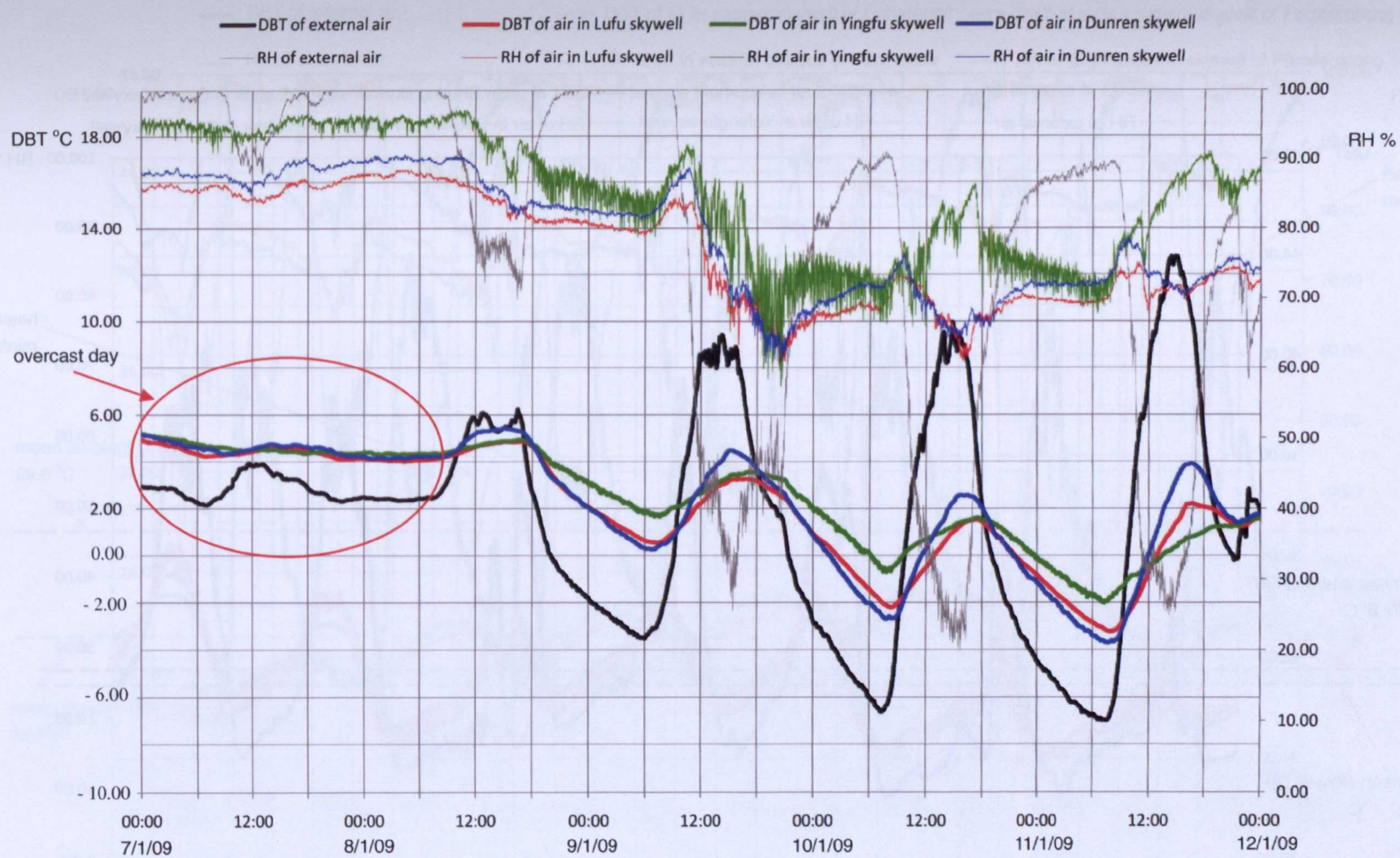


Figure 6. 5 Temperature and relative humidity data for dwellings in Xidi village in winter recording period

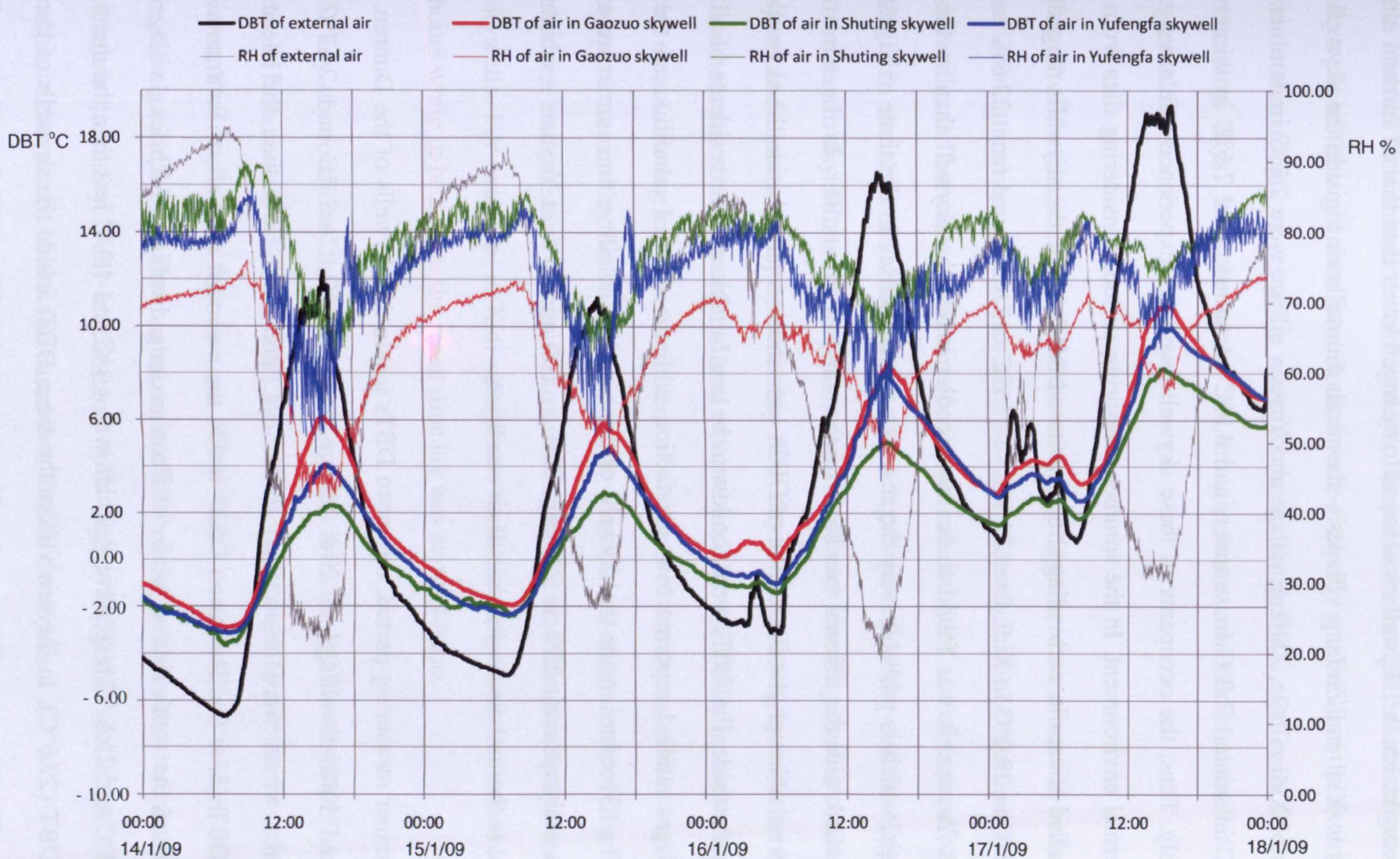


Figure 6. 6 Temperature and relative humidity data for dwellings in Yuyuan village in winter recording period

The fluctuations of DBT and RH inside the skywells of vernacular dwellings was much smaller than the fluctuations of these values measured in the external air. The diurnal swing inside the skywells was found to be much lower than that of ambient air, especially in Xidi and Zhifeng villages – the mean diurnal swing inside the skywell dwellings of Xidi village, Zhifeng village and Yuyuan village were 2.8°C in summer and 3.2°C in winter; 2.0°C in summer; and 4.7°C in summer and 7.6°C in winter respectively. Thus, the occupants of these skywell dwellings experience a relatively stable thermal environment. In the summer measuring period, considering data from all the studied houses in each village, the monitored DBTs inside the skywells ranged from 20.8°C to 29.0°C in Xidi, from 21.9°C to 27.9°C in Zhifeng and from 22.6°C to 32.5°C in Yuyuan. It was found to be much cooler inside the skywell than in the external air, which is probably why the residents of the houses in the three villages were satisfied with the thermal condition of their houses in summer. In the winter testing period although the fluctuation of DBTs were much smaller inside the skywell than that of outside, the DBTs were too low to be comfortable and the residents of all three villages studied reported low satisfaction with the thermal condition of the houses. The RH values inside the skywells of these studied dwellings in summer were very high – always over 85% in Zhifeng, 75% in Xidi and 70% in Yuyuan – which could lead to thermal discomfort in still air condition.

In the summer measuring period, the mean DBTs inside the skywells of the Dunren, Yingfu and Lufu dwellings of Xidi village were 25.0°C, 24.6 °C and 24.7°C respectively, which were respectively 2.6°C, 3°C and 2.9°C less than the mean external DBT (27.6°C). The mean DBTs inside the east side skywell of Panmaotai dwelling, and the south side skywells of Panxianxiong dwelling of Zhifeng village were 25.3°C and 25.6 °C respectively, which was 4.3°C and 4.0°C less than the mean external DBT (29.6°C). In Yuyuan village the mean DBTs inside the skywells of the Yufengfa, Shuting and Gaozuo dwellings were 26.9°C, 27.3°C and 27.1°C respectively; these values were close to the mean external DBT (27.6°C).

On each of the summer recording days, the peaks in the DBT traces obtained in the skywells of the eight dwellings studied were distinctly smaller than the external DBTs while the trough values were close to the external DBTs. On each of the winter recording days, both the peaks and troughs were considerably smaller than the external DBTs.

For all of the houses, on each of the recording days there was found to be a time lag between attainment of maximal external DBT and attainment of maximal DBT in the skywells, and between attainment of minimal external DBT and attainment of minimal DBTs in the skywells. However, the time lag observed in skywell dwellings varied from day to day. While the material properties of each dwelling remain constant, wind speed and direction vary considerably from day to day, leading to variation in the lag time between attainment of maximal external and skywell DBTs. In each of the houses, the mean time lag between attainment of maximal external temperature and maximal temperature in the bedrooms was much longer than the corresponding time lag between attainment of maximal external temperature and maximal temperature in the skywells. For example, in Xidi village the mean time lag in skywells was about 1.5 hours while in bedrooms the mean time lag was about 4 hours.

At any sky condition, the ambient RH reverses with the DBT – when DBT increases, the RH decreases; when the DBT reaches its peak, the RH reaches its trough, vice versa. The reason is as follows – the RH is the ratio of the actual amount of moisture in the air compared to the maximum amount that the same air can contain. When the absolute humidity (AH) is constant, with higher DBT the maximum amount of moisture that can be held is increased thus the RH decreases.

In summary, from the questionnaire and thermal recording data, it can be concluded that in summer the residents appreciate the space within the skywell since it was much cooler than the ambient air. In winter the residents found the skywell unacceptably cold, and found it necessary to take action to maintain the thermal comfort. It can thus be concluded that the design of Chinese vernacular skywell dwellings is mainly intended to counteract excessive summer heat than uncomfortable winter cold (although the presence of only a very small number of openings in the walls of the buildings might in part be a measure to combat extreme winter temperatures by reducing heat loss). Therefore the manner in which the house designs achieve lower sub-external DBTs inside the skywells and general improvement in summer thermal comfort was investigated in depth. The exploration of this topic is described in sections 6.4 – 6.7 below. The following points are considered.

- Why was the fluctuation of DBTs inside the skywell reduced considerably in relation to the external air?
- Why was the mean DBT inside the skywell found to be 2.6 °C – 4.3°C lower than the mean external DBT in Xidi and Zhifeng villages but very close to the mean external DBT in Yuyuan village?

As a thermal system the skywell has the following heat inputs and outputs:

- radiative heat gain/loss
- conductive heat gain/loss
- convective heat gain/loss
- evaporative heat loss
- heat gain from internal sources such as electrical appliances and the bodies of the occupants

In sections 6.4 – 6.7, Chinese vernacular dwellings actively achieve a stable and comfortable thermal environment within the skywell are discussed. The measures taken to achieve winter thermal comfort and their effect are discussed in chapter 7.

6.4 Effect of radiation

Radiant heat gain and loss within the skywell are considered in this section. The effect of solar radiation through the void and opaque structural elements is examined first, and then radiation from external and internal surfaces is discussed.

6.4.1 Solar radiation

Solar heat gain is considered separately for void and opaque elements.

Incident solar radiation into the skywell void

The solar gain within the skywell depends on the solar irradiance, the size of the skywell, and the transmittance of the skywell glazing, if present. When the skywell is small, the amount of solar radiation penetrating into a skywell dwelling is restricted. The amount of solar radiation which penetrates into the skywells of the eight studied dwellings was estimated using Ecotect software. The results are shown in table 6.1.

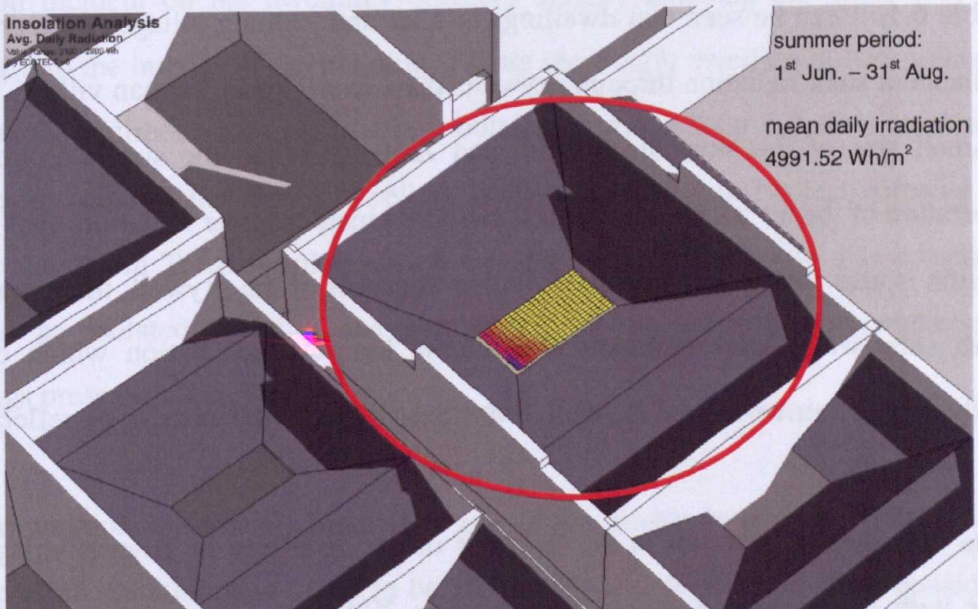


Figure 6. 7 Average daily irradiation incident on Yingfu skywell in the summer period

Table 6. 1 mean daily solar irradiation Q incident upon the skywells in the summer period (1st Jun – 31st Aug) for the eight dwellings studied (where Q derived from proximal weather station data and Ecotect software)

village	dwelling names and designations of skyells (in parentheses)		dimensions LXWXH (m)	WI	mean daily incident solar irradiation on the skywell (Q) unit: KWh
Yuyuan	Gaozuo dwelling (W1)		9.3X5.8X5	0.7	219.2
	Shuting dwelling (W2)		6.1X5.2X5.3	0.94	128.9
	Yufengfa dwelling (W3)		9.2X2.95X4.9	1.1	110.3
Xidi	Dunren dwelling	eastern skywell (W4)	4.3X2.15X5.26	1.83	41.4
	Yingfu dwelling (W5)		4.2X1.8X6.8	2.7	33.9
	Lufu dwelling	eastern skywell (W6)	3.3X1.35X7.8	4.07	20.0
Zhifeng	Panxianxiong dwelling	northern skywell (W9)	1.8X0.75X6.3	5.95	5.7
		southern skywell (W10)	1.1X0.75X6.2	6.95	3.5
	Panmaotai dwelling	eastern skywell (W11a)	1.1X0.6X6	7.73	2.8

In table 6.1, it can be seen that dwellings in Xidi and Zhifeng villages receive much less incident solar radiation through skywells than dwellings in Yuyuan village, due to the small size of the skywells in Xidi and Zhifeng. When the sun is shining the temperature of the air within a skywell is raised by incident solar radiation. Part of this radiation is also absorbed by the construction materials of the skywell; these materials absorb short-wave solar radiation and release long-wave radiation which can be absorbed by the air within the skywell. Some heat is lost to the exterior by reflection.

In site measurements the air in the skywells of the dwellings in Yuyuan village was hotter with larger diurnal swing than those in Xidi and Zhifeng even though the ambient air in Yuyuan was slightly cooler than that in Xidi and Zhifeng. The dwellings in Yuyuan village receive a large amount of solar radiation through their large skywells; and the thermal environment within them is more influenced by solar radiation than the air in the skywells in Zhifeng and Xidi (see figures 6.2 – 6.4).

Opaque element (indirect solar radiation)

The heating of a surface by solar radiation depends on solar irradiance and the absorption of solar heat energy. This heat input will elevate the surface temperature which will cause more heat flow into the interior through the construction elements – mainly walls and roofs.

1) Reflectance

Using the light meter, the mean reflectance of the external white wall surface was calculated to be 0.62. The light colour of the external wall surfaces increase the reflection of solar radiation, thus reducing the heat absorbed by the dwellings.

2) Mutual shading

As discussed in section 3.4.2, the dense arrangement of most of the houses in the village results in mutual shading. This greatly reduces the amount of direct solar radiation incident on the dwellings' surfaces thereby reducing the amount of heat flowing into the interior of the building. Taking the Yingfu dwelling in Xidi village as an example, indirect solar gain (the heat obtained through solar radiation incident on opaque surfaces) of the Yingfu dwelling was simulated using Ecotect software and climate data from Tunxi weather station (see figure 6.8). The house was considered both as an isolated building and surrounded by the immediately neighbouring buildings present in Xidi village.

In the simulation, the mean indirect solar gain of the Yingfu dwelling in summer when considered in isolation was found to be 16.62KWh and 10.87KWh when considered as a building within a group. Thus, mutual shading was found to reduce indirect solar gain by 35% in summer, when solar heat gain needs to be minimized.

The extent of indirect solar gain depends on various factors including the properties of construction materials, solar radiation, solar absorption of the surface material and external air temperature. Mutual shading was the only factor that was varied in the simulation, and it was shown to have a large effect.

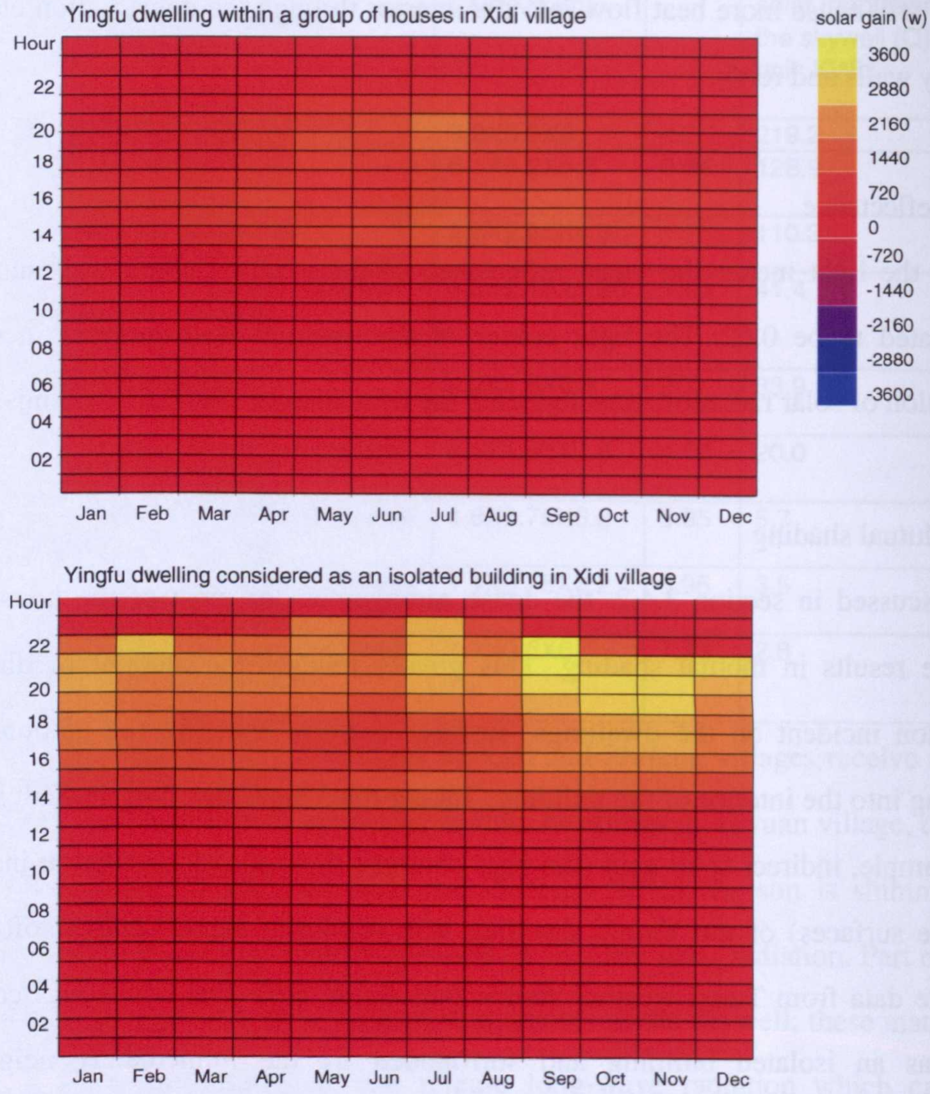


Figure 6. 8 Monthly averages of indirect solar gain in each of the 24 hours in Yingfu dwelling alone and within a group of houses in Xidi village

3) Effect of the Horse-head wall

Besides providing security and restricting the spread of fire from adjacent houses, the tall horse-head wall also shades the roof and internally provides significant thermal capacitance which helps to stabilise internal temperatures.

6.4.2 External surface radiation

Radiation to the sky

Vernacular dwellings absorb radiant solar energy in the daytime, and lose heat by radiation over the whole day. At night, the long-wave infrared radiation emitted from the warm surface of the dwellings exceeds the long-wave infrared radiation from the clear, cold sky onto the dwelling. Radiant cooling can be assumed to occur in the cool summer night in the villages studied.

The sloped roof is a very common feature in Chinese vernacular skywell dwellings. A sloped roof has a larger area from which radiation can be emitted than a flat roof but the area over which direct solar radiation can be received remains the same (for example the emitting area is increased by about 9.4% for a roof with a 25° slope). Thus, with a sloped roof, the solar gain through the roof is not increased in the daytime but the heat loss due to radiant cooling is increased in the night.

The sloped roof is partially sheltered from direct sunlight by the horse-head wall, reducing solar gain in the daytime.

Radiation to the surroundings

Since the roof of vernacular dwellings has the greatest exposure to the cold sky of any structural element of the building, the largest amount of radiant cooling occurs through the roof while radiative heat transfer between the wall surfaces of closely apposed buildings can be disregarded. These surfaces experience almost identical thermal condition, so they will always be of similar temperature, and little transfer of heat can occur between them.

6.4.3 Radiation from internal surfaces of skywells

The temperature of the internal surfaces within a skywell dwelling is raised by the penetrating sunlight. The materials that make up the surfaces then emit long-wave infra-red radiation; this is absorbed by the air within the skywell, raising the temperature of that air. The skywell floor faces the sky directly, which can also lead to effective radiant cooling in cool summer nights.

6.4.4 Summary

The amount of solar radiation penetrating into a skywell dwelling is restricted when the skywell is narrow. The tall white horse-head wall and mutual shading of vernacular dwellings can reduce indirect solar gain considerably. Heat is also emitted by surface radiation from the dwelling; radiant cooling is important at night when the sky is cold and clear, especially through the roof and from the area of the skywell floor directly under the skywell aperture.

The thermal environment within the skywell is not influenced directly by the solar gains incident on the opaque elements – it is influenced in the form of conduction from the external surface whose temperature is raised by solar illumination. Heat flows from the external surface into the interior. Conductive heat gain is discussed in section 6.5 below.

6.5 Effect of conduction

In the hot summer daytime, conductive heat gain within the skywell arises from the high external surface temperature of the house and the high external air temperature.

The design of Chinese vernacular dwellings minimizes indirect solar gain by the shading effect of white horse-head walls and the surrounding dwellings. The construction materials of vernacular dwellings have low thermal conductance and high thermal mass, which together reduce the peak thermal load and the total heat gain by storing a lot of heat, and delay the entry of the heat into the interior (see 6.5.1 below).

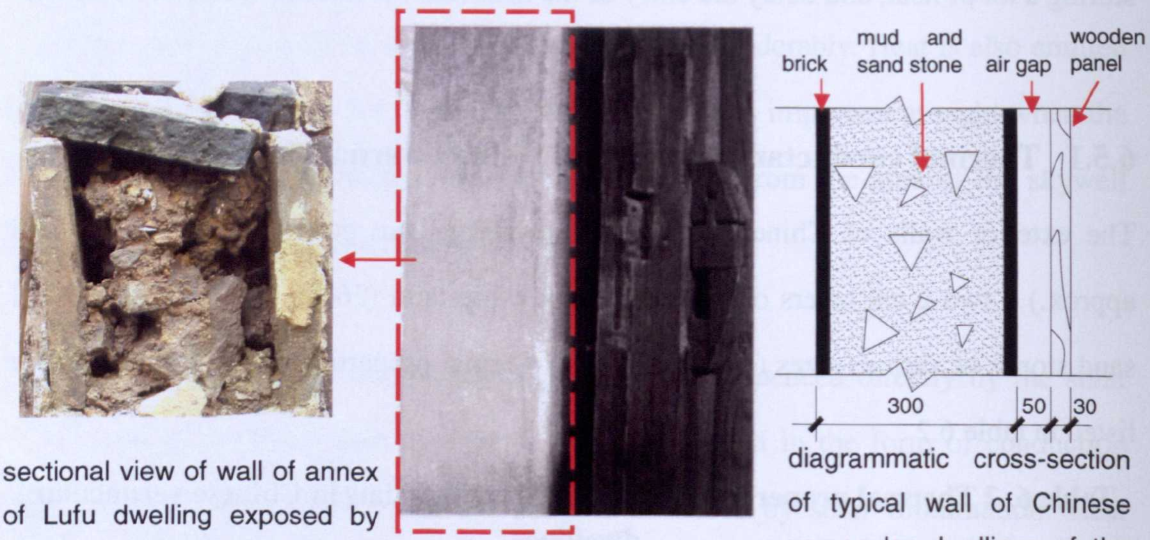
6.5.1 Thermal conductance of walls of Chinese vernacular dwellings

The exterior walls of Chinese vernacular dwellings are generally thick (300 mm approx.) – two 2 cm layers of brick enclose a wide void (26cm) filled with mud and sand stones of various sizes (figure 6.9). The thermal properties of these materials are listed in table 6.2.

Table 6. 2 Thermal properties and densities of materials in Chinese vernacular dwellings

	thermal conductivity (W/mK)	density (kg/m^3)	specific heat (J/kgK)
brick	0.62	1700	800
sandstone	1.3	2000	800
mud	1.25	1600	1000
timber	0.115	544	1220
air	0.025	1.15	1063

The bedrooms in the dwelling do not directly abut the exterior wall; there is a 50 mm air gap between the wall and the wooden panels lining the room. The air gap provides further insulation, reducing heat gain in summer and heat losses in winter. The thermal conductivities of air and timber are also listed in table 6.2. Using measurements of the thickness of the components of the wall of the Lufu dwelling in Xidi village and the data in table 6.2, the thermal conductance of the walls was calculated to be 1.8 W/m^2K excluding the contribution of the inner boarding and the air space, and 0.36 W/m^2K with the inclusion of the inner boarding and the air gap in the calculations (a 2mm thick layer of air was assumed to be present in the walls to allow for the air spaces in the sand stones layer). The 50 mm air gap between the wall and the wooden panel lining the room is the main contributor to the low thermal conductance (0.36 W/m^2K); however, the air gap is not sealed, so this low thermal conductance might not be achieved.



sectional view of wall of annex of Lufu dwelling exposed by damage, showing two layers of brick and core of sand stones

diagrammatic cross-section of typical wall of Chinese vernacular dwellings of the types investigated in the present study

Figure 6. 9 Composition of walls of Chinese vernacular dwellings

Diurnal fluctuation in the temperature of the air in the bedrooms of the eight dwellings studied lagged behind those observed in temperatures measured in the skywells. Fluctuations in bedroom air temperature were also smaller. The lower thermal conductance of bedrooms due to the air gap and the interior wooden panels contribute to the time lag. Another reason for the lag is that with direct openings (doors and skywell) to the outside, the air exchange rate within the skywell is more frequent than the exchange rate within bedroom since only small opening facing the skywell is present in the bedroom if it is fully opened (figure 6.10).

Figure 6. 10 Large openings to the outside and small openings of bedroom to the skywell

Furthermore, the annexes (such as the kitchen and the toilet) which adjoin the external walls act as buffers which provide further insulation for the whole dwelling.

6.5.2 Thermal mass

Building materials of low thermal conductance retard heat transfer and cause a lag between fluctuations in external and internal temperatures. The amount of heat transferred, as well as the rate of heat transfer, is also influenced by the thermal mass of building materials.

In table 6.2, it can be seen that the construction materials in vernacular dwellings have high density and specific heat. Szokolay (2008) classifies buildings into either two or three categories according to specific mass (total mass divided by total floor area) a building can be considered as heavyweight if the specific mass (kg/m^2) of the building (total mass of the building divided by total floor area of the building) achieves the following criterion for two or three divisions:

Light	<150 kg/m^2
Medium	150–400
Heavy	>400
Light	≤ 250 kg/m^2
Heavy	>250

Using the density data given in table 6.2 and measurements of the thickness of wall components, the specific mass of the type of wall encountered in the eight dwellings studied in detail and illustrated in figure 6.9 was calculated to be over 400 kg/m^2 (eg. 680 kg/m^2 in the Yingfu dwelling). The massive structure of Chinese vernacular dwellings acts as a heat sink. With their high heat capacity, the walls and floor absorb heat during the summer day and release it during the night. Thus, heat is stored in the construction materials and its entry into the dwelling delayed. This leads to the reduction of the temperature fluctuation inside the skyell markedly.

6.6 Effect of convection

6.6.1 Ventilation

As discussed in section 3.4.2, residents prefer to keep the external doors of traditional houses open in summer to remove both the smells and excessive heat; while in winter, residents keep the doors closed to minimise heat losses.

Mode of ventilation within Chinese vernacular skywell dwellings

Through site measurement, it can be found that cross ventilation mostly occurred in the vernacular dwellings in the daytime with the doors open while the stack effect ventilation occurred mainly during the night with all the doors closed.

In figure 6.11 the principal mode of ventilation in Chinese vernacular dwellings – cross ventilation – is shown in the Dunren dwelling. Cross ventilation in this dwelling is displayed here as an example; cross ventilation in the other dwelling studied is illustrated in appendix D. In figure 6.11 the arrows indicate the estimated and approximate prevailing direction of air flow at the time of measurement.

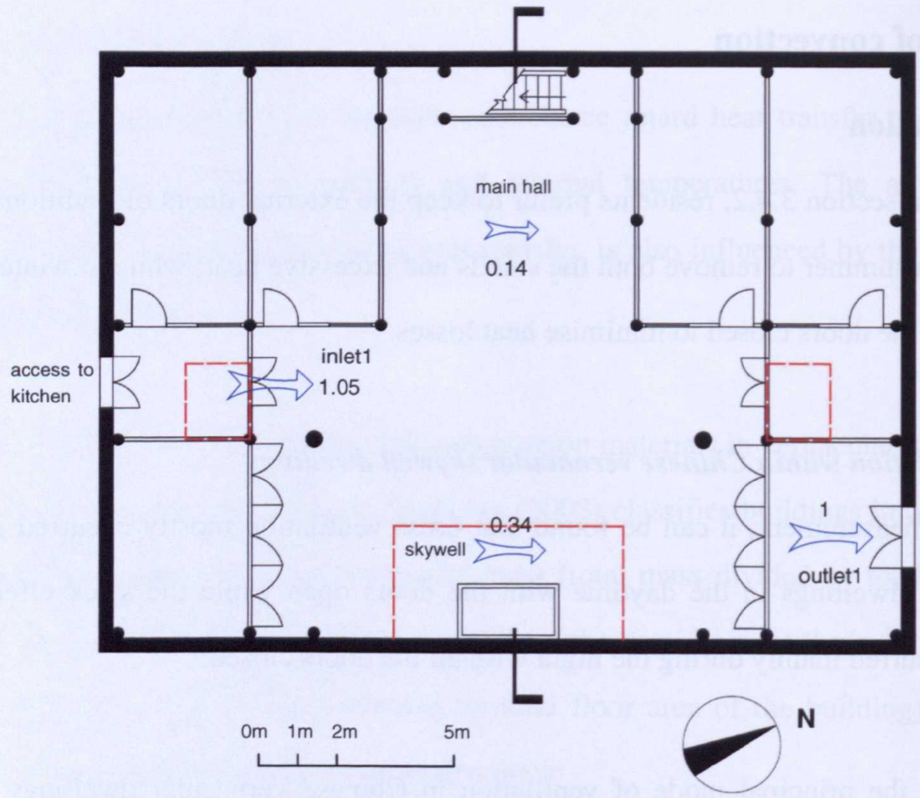


Figure 6. 11 Mean air speeds at different points in the Dunren dwelling as a proportion of mean air speed in main entrance measured at the same time

The vernacular dwellings investigated in the present study differ in the number of inlets and outlets they possess. On-site data on air speed obtained in the daytime during the summer measuring period for each of the eight dwellings studied are displayed in table 6.3. Air speeds used to calculate the results in table 6.3 were measured with all inlets and outlets. Inlets and outlets were defined according to prevailing direction of air flow at the time of recording. In table 6.3 all air speeds are horizontal unless noted.

Table 6. 3 Mean air speeds at different locations in dwellings as a proportion of air speed in main entrance in the eight vernacular dwellings studied during the daytime in the summer testing period

village	dwelling	inlet air speed		outlet air speed as proportion of wind speed at main entrance				air speed in hall as proportion of wind speed in main entrance	air speed under skywell as proportion of wind speed in main entrance	vertical air speed under skywell as proportion of wind speed in main entrance
		inlet1	inlet2	outlet1	outlet2	outlet3	outlet4			
Yuyuan	Gaozuo dwelling	1.47		0.51	0.69	1.00		0.02	0.21	0.01
	Shuting dwelling	2.08		0.68	1.72	1.00	1.51	0.21	0.57	0.05
	Yufengfa dwelling	1.63		1.22	1.00			0.19	0.50	0.07
Xidi	Dunren dwelling	1.05		1.00				0.14	0.34	0.09
	Yingfu dwelling	1.00		0.56				0.01	0.15	0.04
	Lufu dwelling	1.38		1.00	0.52			0.02 (eastern hall)	0.08 (eastern skywell)	0.05 (eastern skywell)
								0.15 (western hall)	0.79 (western skywell)	0.01 (western skywell)
Zhifeng	Panxianxiong dwelling	1.26	1.24	1.00				0.20 (southern hall)	0.11 (southern skywell)	0.03 (southern skywell)
								0.11 (northern hall)	0.68 (northern skywell)	0.10 (northern skywell)
	Panmaotai dwelling	1.00		1.12				0.19(eastern hall)	0.12 (eastern skywell)	0.02 (eastern skywell)
								0.08 (western hall)	0.07 (western skywell)	0.03 (western skywell)

It can be seen that air speeds at the inlets and outlets were much higher than those in the skywell; in the hall, air flow was very weak. Horizontal air speeds directly below the skywell, which are close to the main axes of air flow between the inlet and outlet to the buildings were higher than the speeds measured at points far from the axes. Vertical air speeds directly below the skywell were very low.

It can be concluded from the low vertical air flow observed below the skywells of all the dwellings that little stack effect ventilation occured during the daytime. This is because the external air temperature is higher than the air temperature inside the skywell through most of the daytime.

Air flow was measured between 0:00 and 00:30 in the Yingfu and Lufu dwellings on the 29th and 30th Aug 2010. The mean vertical air speed directly below the skywell of the Yingfu dwelling was 0.11 ms^{-1} while that below the eastern skywell of the Lufu dwelling was 0.19 ms^{-1}. (The mean value below the glazed western skywell of Lufu dwelling was 0.02 ms^{-1}). The predicted night air flow pattern in Chinese vernacular skywell dwellings is shown in figure 6.12 (taken Dunren dwelling as an example). The vertical air flows below the skywells were relatively stable. Mean air speeds were low at night but much higher than those measured in the daytime. It can be concluded that stack effect ventilation occurred at night but not to any appreciable extent in the daytime. During the night the air in the skywell of a traditional dwelling is usually warmer than the outdoor air. The walls and floor of the skywell have been receiving solar radiation throughout the day, so their temperature increases and the enclosed air becomes warm. This would establish convection currents.

Dense cold air from the external environment enters the skywell from the top and descends to the bottom of the skywell. Within the skywell it is warmed, becomes less dense and moves upwards. In these convection currents cold air moves down the centre of the skywell and warm air ascends close to the walls. Cold outdoor air may also enter a skywell house by leakage through the external doors.

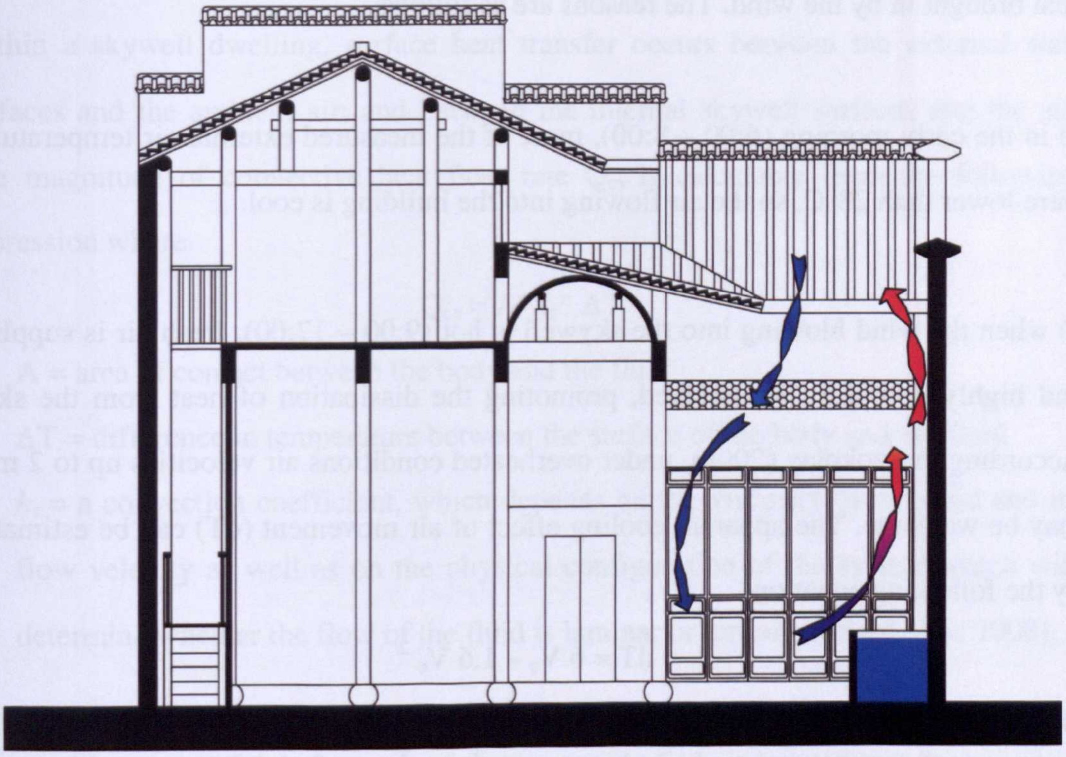


Figure 6. 12 Night air flow pattern in Dunren dwelling of Xidi village

Effect of wind

For the eight dwellings studied, the temperature of wind blowing into the buildings from the adjoining streets or alleyways was lower than the external air temperature in the daytime – mean spot measurements of air temperature within the streets or alleys were about 2.8 °C less than mean concurrent external values recorded by data logger. This is due to mutual shading by the densely arranged dwellings.

It was found that the temperature of the air outside the dwelling was higher than the temperature of air in the skywell through most of the daytime. Hot wind could raise the temperature of the house, and thus be disadvantageous. However, in interviews, most residents like the air flow and prefer to the keep the doors open in summer (most residents open the doors between 6:00 and 7:00 in the early morning once they get up and close the doors between 18:00 and 19:00 when the sky becomes dark) despite the heat brought in by the wind. The reasons are as follows.

1) in the early morning (6:00 – 8:00), most of the measured external air temperatures were lower than 28°C, so the air flowing into the building is cool.

2) when the wind blowing into the skywell is hot (9:00 – 17:00), fresh air is supplied and highly humid air is removed, promoting the dissipation of heat from the skin. According to Szokolay (2008), under overheated conditions air velocities up to 2 ms^{-1} may be welcome. The apparent cooling effect of air movement (dT) can be estimated by the following equation.

$$dT = 6\ V_e - 1.6\ V_e^{\ 2}$$

Where V is the air velocity (ms^{-1}) at the body surface Ve is the effective air velocity, which is equal to V – 0.2, and dT (°C) is the cooling effect. The expression is valid up to 2 ms^{-1} (Szokolay, 2008). With a meadured air velocity of 0.62 ms^{-1} in the skywell of the Dunren dwelling in August the cooling effect dT is about 2.3°C. This extends the upper limit of thermal comfort in this house by 2.3°C.

3) the movement of air through the skywell also enhances evaporation within the skywell, and hence evaporative cooling. This will be discussed in section 6.7.

6.6.2 Surface heat transfer

Within a skywell dwelling, surface heat transfer occurs between the external wall surfaces and the ambient air; and between the internal skywell surfaces and the air. The magnitude of convective heat flow rate Q_{cv} is calculable from the following expression where

$$Q_{cv} = A * h_c * \Delta T$$

A = area of contact between the body and the fluid

ΔT = difference in temperature between the surface of the body and the fluid

h_c = a convection coefficient, which depends on the viscosity of the fluid and its flow velocity as well as on the physical configuration of the system which will determine whether the flow of the fluid is laminar or turbulent (Szokolay, 2008).

As noted in section 6.6.1, for each of the houses studied air temperature measured in the street or alley adjoining the dwelling was lower than the external air temperature; this is because of mutual shading. The temperatures of the external wall surfaces within the alley were lower than that of the exterior air due to shading. When a hot wind blows into the alley, the convective heat transfer occurs from the hot wind to the relatively cool external wall surfaces, cooling the hot wind. The air movement would enhance this heat transfer considerably.

The internal and external surface temperatures of the eight vernacular dwellings studied were measured. In figure 6.13 the results of the measurement in the Dunren dwelling are shown as an example. Value of surface temperatures of wall, ground floor and roof were shown in table 6.4.

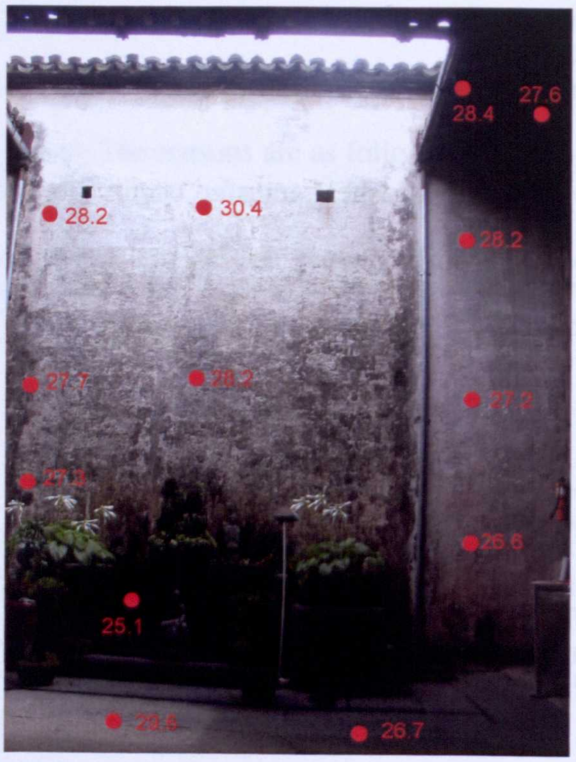


Figure 6. 13 Surface temperatures within the Dunren dwelling at 12:00 on 2nd Sep 2010

Table 6. 4 Surface temperature of wall, ground floor and roof within skywell of the Dunren dwelling on 2nd Sep 2010and the early morning of 3rd Sep 2010

time	external DBT(°C)	internal DBT(°C)	inner surface temp. of the wall (°C)	external surface temp. of the wall (°C)	surface temp. of skywell ground floor (°C)	inner surface temp. of roof (°C)
09:00	32.3	26.7	26.1	36 (under the light)	24.8	25
12:00	34.9	28.3	28.5	37(under the light)	27.6	28.2
15:00	33.7	28.5	28.3	31	27	27.1
18:00	28.9	27.6	26	27	25	25.4
06:00 (next day)	25.1	25.4	23.6	24	23	22.9

The air temperature inside the Dunren skywell was higher than that of the internal skywell surface at 9:00, 15:00, 18:00 and 6:00 but not at 12:00 when solar radiation was strong. At night, the temperature of air within the skywell of the Dunren dwelling was found to be close to those of the surfaces of the structural elements surrounding the skywell (the inner and outer surface of the skywell wall, the inner surface of the roof, the skywell floor (table 6.4). However, the internal surface temperatures fell by more than 2°C between 18:00 and 06:00. This is probably because of evaporation at the internal skywell surfaces. This will be discussed in section 6.7.

6.7 Effect of evaporation

During the summer testing period, evidence of evaporation was found in skywell dwellings of Xidi and Zhifeng villages but not in Yuyuan village. Evaporation can reduce the air temperature inside the skywell markedly, given the high latent heat of vaporisation of water. With 1g water evaporated, the amount of energy used is about 2400J. This amount of energy could reduce 1kg of air by 2.4°C. The absolute humidity (AH) inside and outside the skywells of the studied dwellings was calculated through the use of CYTPsyChart software (CYTSoft Technology, USA) based on the DBT and RH data obtained by site monitoring.

6.7.1 Results

During the summer measuring period, the AH in the ambient air in the three villages were very high – more than 16g/kg in Zhifeng, 15g/kg in Xidi and 17g/kg in Yuyuan. The time course of AH inside and outside the skywells was similar to that of DBT – peak values of AH were observed around noon time and the trough values were observed before the sun rose, since evaporation increases with temperature, raising the AH of the air (figure 6.14 – 6.16).

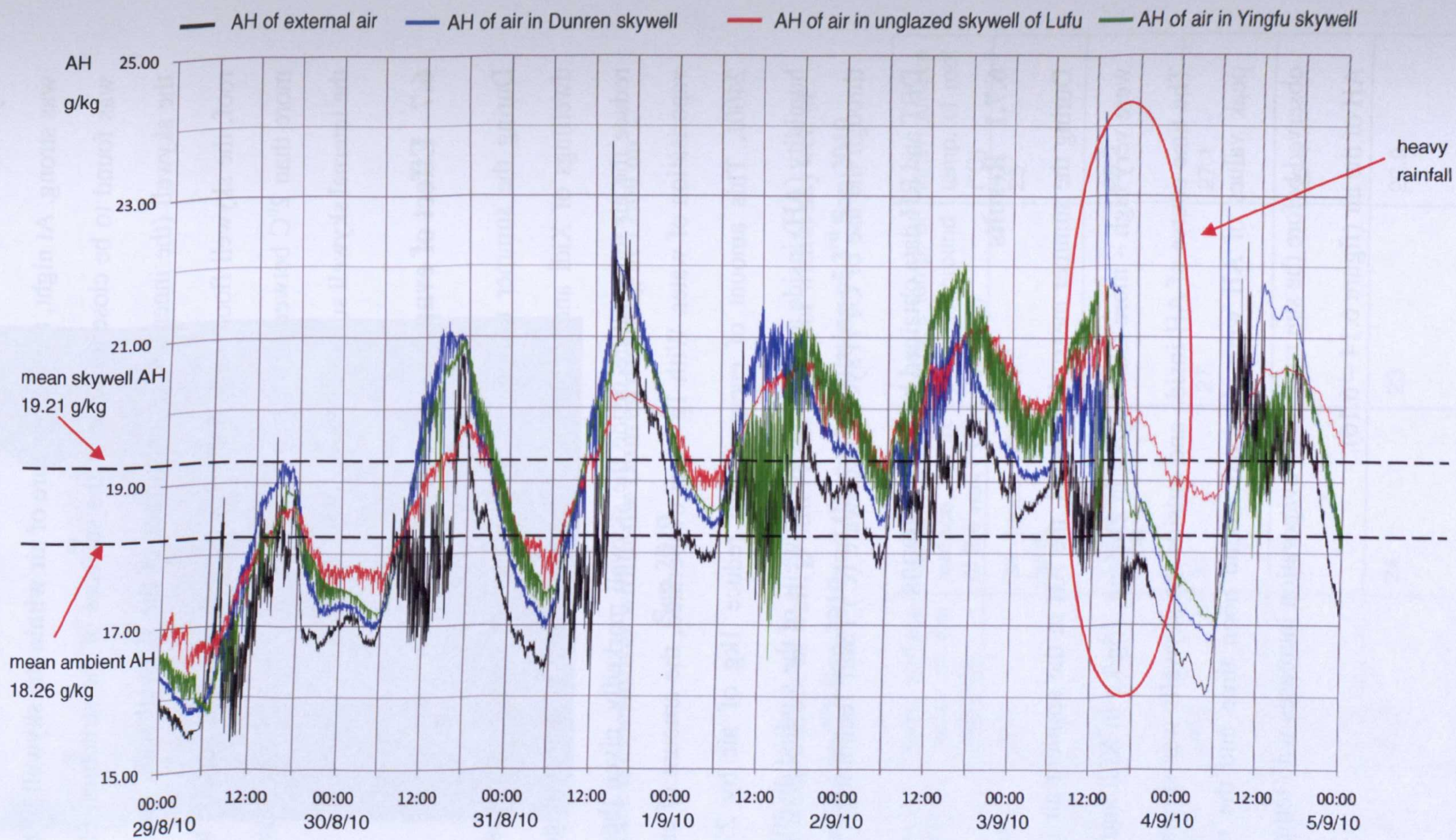


Figure 6. 14 Absolute humidity data for dwellings in Xidi village in summer recording period

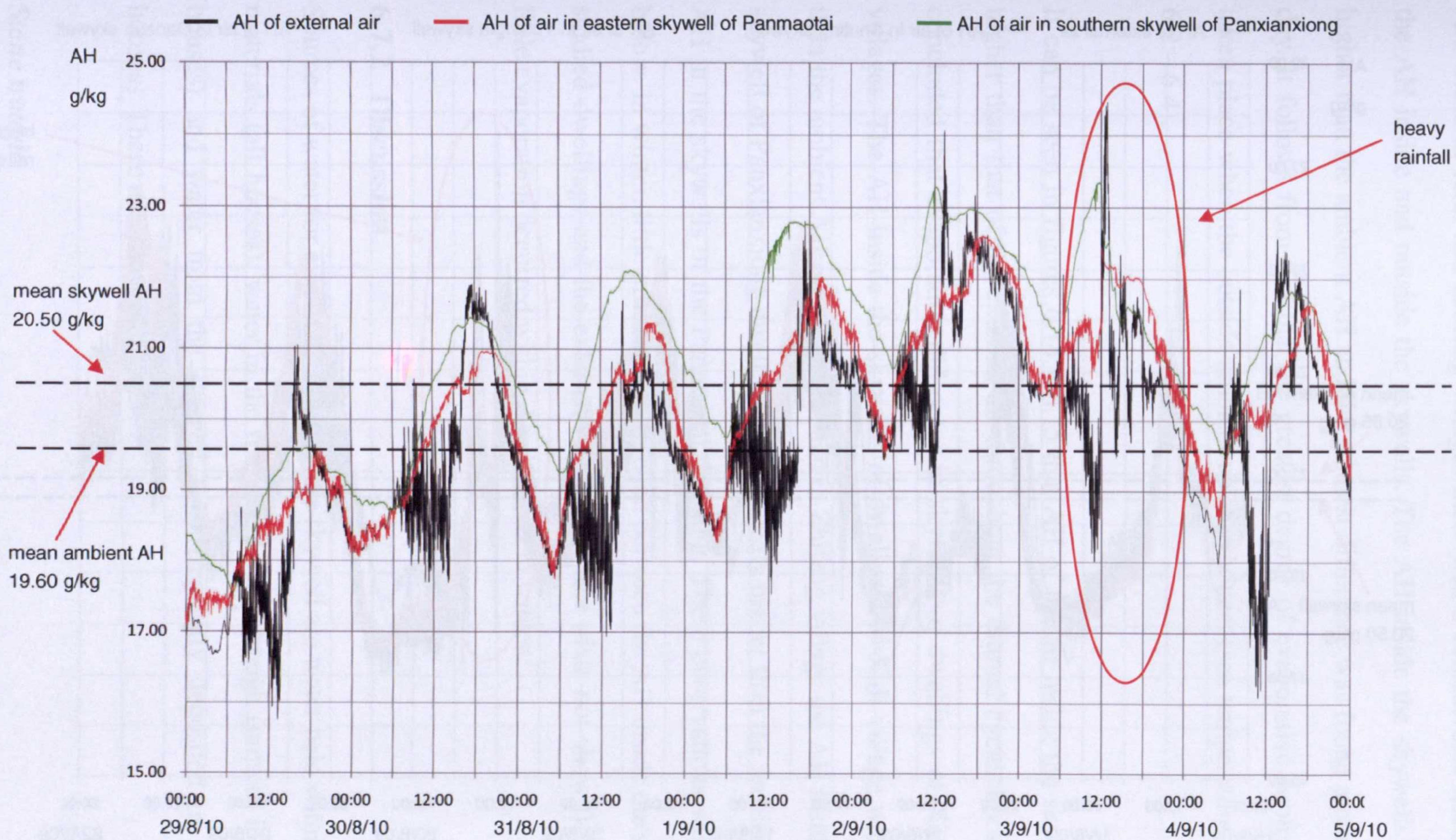


Figure 6. 15 Absolute humidity data for dwellings in Zhifeng village in summer recording period

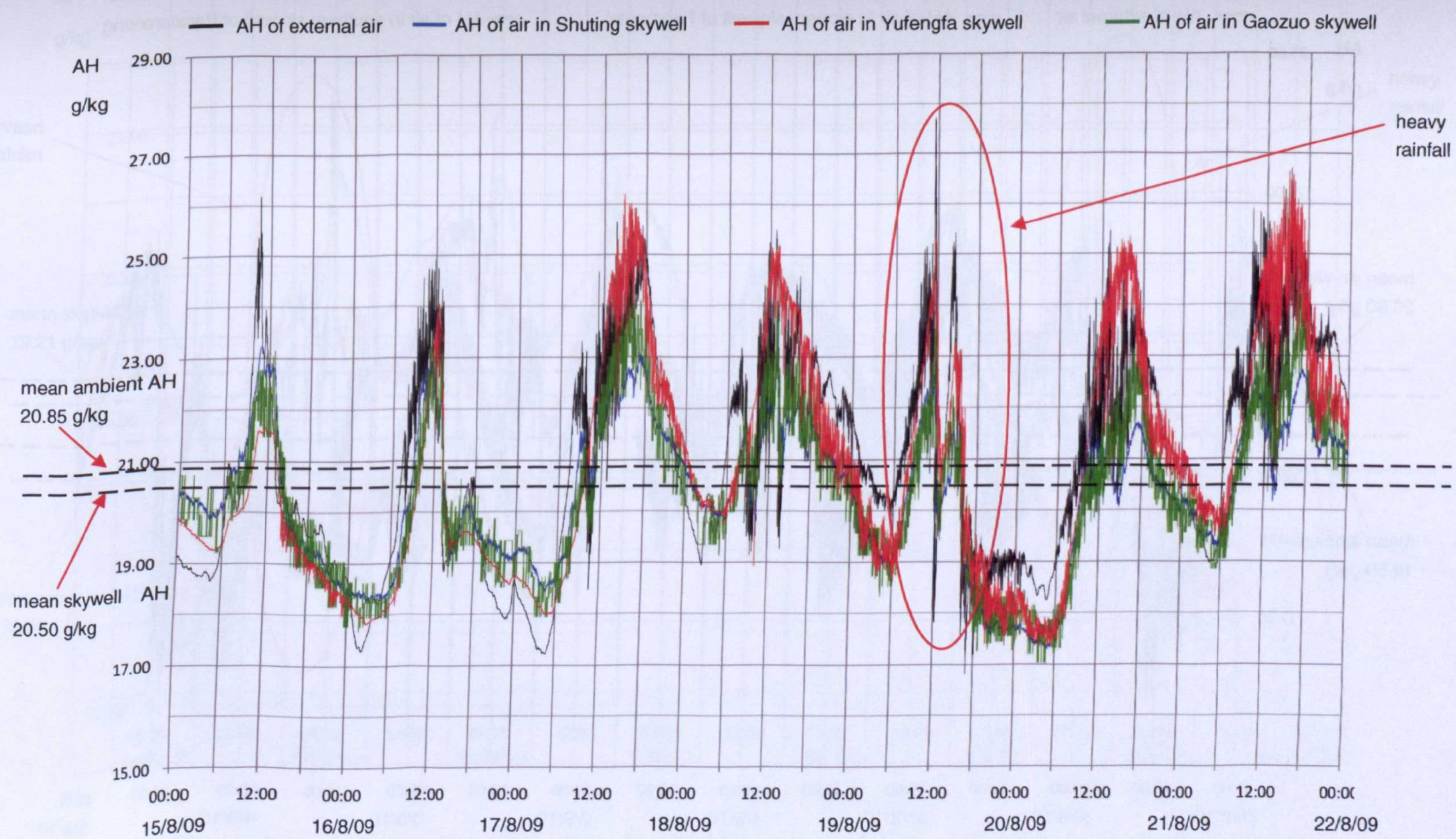


Figure 6. 16 Absolute humidity data for dwellings in Yuyuan village in summer recording period

In Yuyuan village, the AH inside the skywell dwellings was very close to the ambient AH while in Xidi and Zhifeng villages there was a considerable difference between the AH inside and outside the skywells. The AH inside the skywells was generally higher than the ambient AH and the greatest difference was found around 12:00 every day. It follows from this that the greatest degree of evaporative cooling would have taken place when the outside ambient air was hottest (see temperature data in figures 6.2 – 6.4).

It can be seen in figures 6.14 – 6.15 that AH of the air inside the skywell is usually higher than that of the external air throughout the diurnal cycle. It can therefore be concluded that evaporation did occur in skywells of dwellings of Xidi and Zhifeng villages. The AH inside the skywells of dwellings of Xidi village was much higher than the ambient AH even at night; and in Zhifeng village the AH inside the southern skywell of Panxianxiong dwelling was markedly higher than the ambient AH, and the AH in the skywells of the Panmaotai dwelling. These observations will be explained below. In winter, little difference was found between the AH inside the skywells of the studied dwellings and the external AH at any time (data not shown). It follows that little evaporation occurred within the skywells in winter.

6.7.2 Discussion

Sources of water for evaporation within the skywell are water held within construction materials (all houses), water in the traditional stone trough (present in most skywell houses) and water from the skywell floor (regularly deposited in some skywell houses). These are discussed below.

Stone trough

In traditional Chinese skywell dwellings rainwater is collected in a stone trough at the foot of the skywell (see figure 4.10).

Water contained in construction materials

The construction materials of vernacular dwellings investigated in the present study are hygroscopic, which can accumulate rainwater (when exposed to the external environment) and atmosphere water vapour (from the internal and external environment). A piece of grey brick wall material and a piece of floor material (both obtained as loose fragments) (figure 6.17) were dried in a microwave oven, weighed, immersed in water for 24 hours and reweighed. The grey brick was found to absorb 19.1% of its dry weight during the immersion period and the floor material 14.2%. Unpainted and untreated cedar, the most commonly used wood in the fabrication of the panels and columns of the houses investigated in the present study, has been shown to be able to absorb more than 100% of its mass in water. Water can be absorbed and released by these hygroscopic materials according to the temperature and humidity of the air.

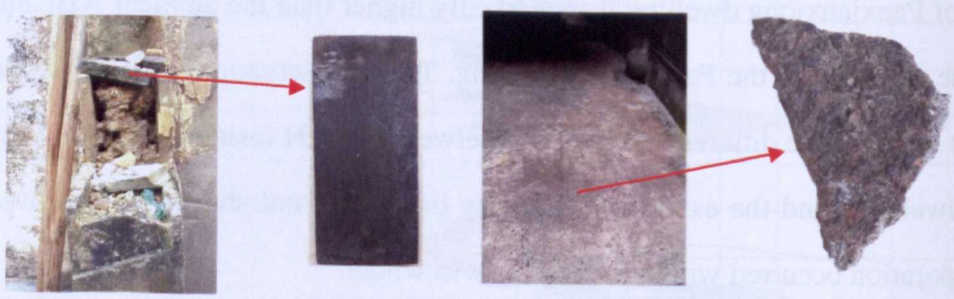


Figure 6. 17 Samples of wall and floor material in Chinese vernacular dwellings

Water from skywell floor

The residents of skywell dwellings sometimes pour water on the skywell floor in summer. In the Yingfu dwelling in Xidi village, occupants always wash their clothes in the skywell and pour the washing water on the ground floor (figure 6.18). Occupants of the Panxianxiong dwelling in Zhifeng village pour waste water into a form of small trough consisting of a number of eight thin flat pieces of stone arranged vertically (figure 6.19). Within the boundary of the trough there is a hole in the floor. Waste water from the trough drains through the hole and into the underlying void.

Figure 6. 18 Additional water sources from washing clothes in skywell of Yingfu dwelling (Xidi village)

Figure 6. 19 Waste water poured into trough made of flat pieces of stone by residents of Panxianxiong dwelling (Zhifeng village)

In some houses investigated in the present study, there was found to be more than one source of water for evaporation in the skywell. These cases are discussed below.

Water for evaporation from water trough and skywell wall combined

Since water for evaporation could come from the water trough and the hygroscopical materials lining the skywell (the wooden panels, the brick walls, the floor materials), it is difficult to distinguish the effect of these sources in isolation in increasing the AH within the skywell. Some useful information about the combined effect of the water trough and the skywell wall was obtained from the Lufu dwelling of Xidi village.

In the Lufu dwelling, the western skywell is glazed but does not contain a water trough while the eastern skywell contains a water trough and is unglazed. A total of 8 data loggers were placed in the skywells recording DBT and RH data over the 7 day summer recording period (figure 6.20). The AH values within the eastern and western skywells are shown in figure 6.21

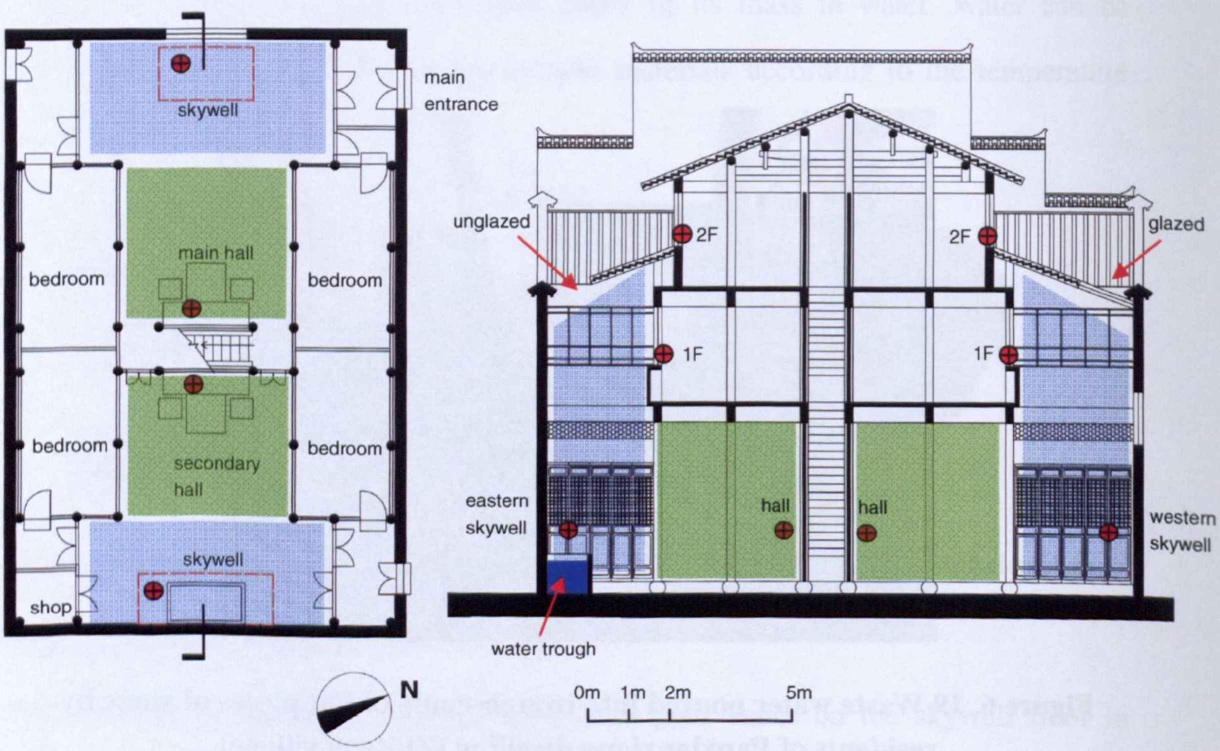


Figure 6. 20 Plan and section of Lufu dwelling (Xidi village) showing the position of data loggers

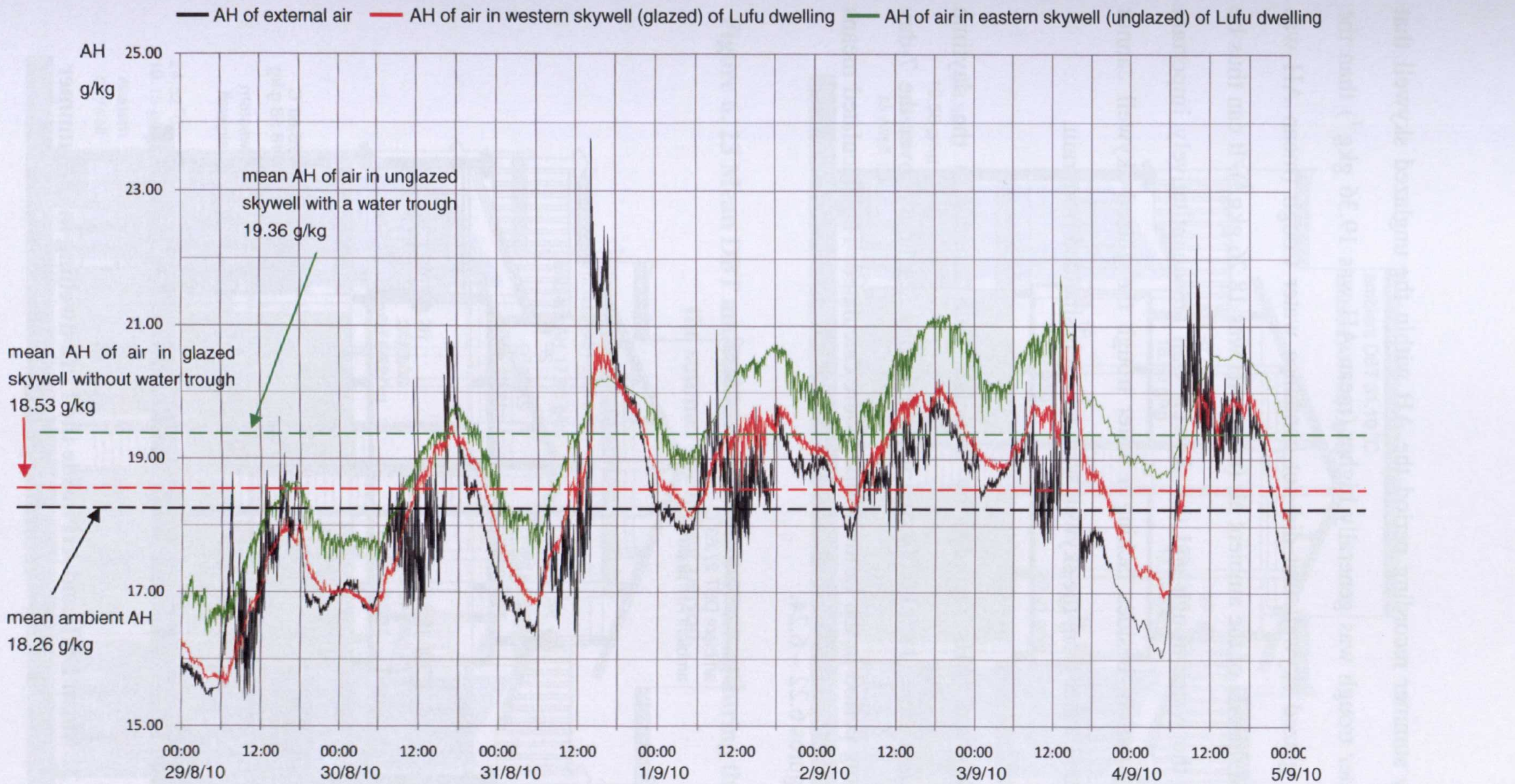


Figure 6. 21 Absolute humidity values within the eastern and western skywells of Lufu dwelling (Xidi village) during the summer recording period

Over the 7 day summer recording period the AH within the unglazed skywell that contained a water trough was generally higher (mean AH was 19.36 gkg^{-1}) than the AH within the glazed skywell that did not contain a water trough (mean AH was 18.53 gkg^{-1}) and the AH of the ambient air (mean AH was 18.26 gkg^{-1}). It can thus be concluded that the water trough and the skywell wall are quantitatively important sources of evaporation; besides lacking a water trough the glazed skywell cannot receive evaporated water from the skywell wall, which is shielded from rain.

The mean DBTs and AHs recorded by the eight data loggers in the daytime (6:00-18:00), night time (18:00-6:00) and the whole day (24 hours) over the 7-day summer recording period in the Lufu dwelling were calculated. The calculated means are shown in figures 6.22 – 6.24.

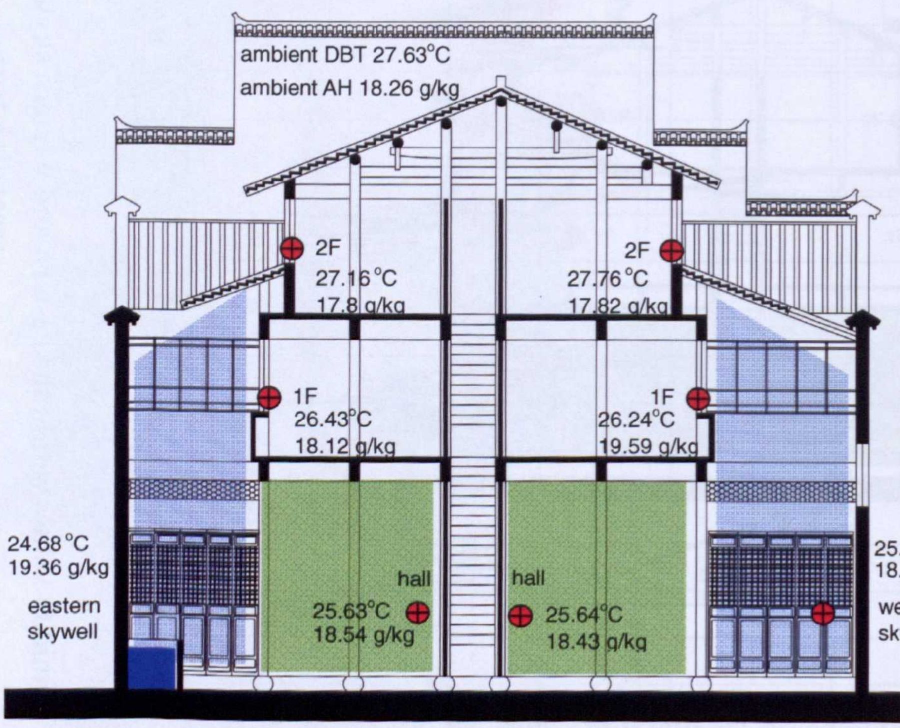


Figure 6. 22 Mean DBT and AH inside the Lufu dwelling in the summer recording period

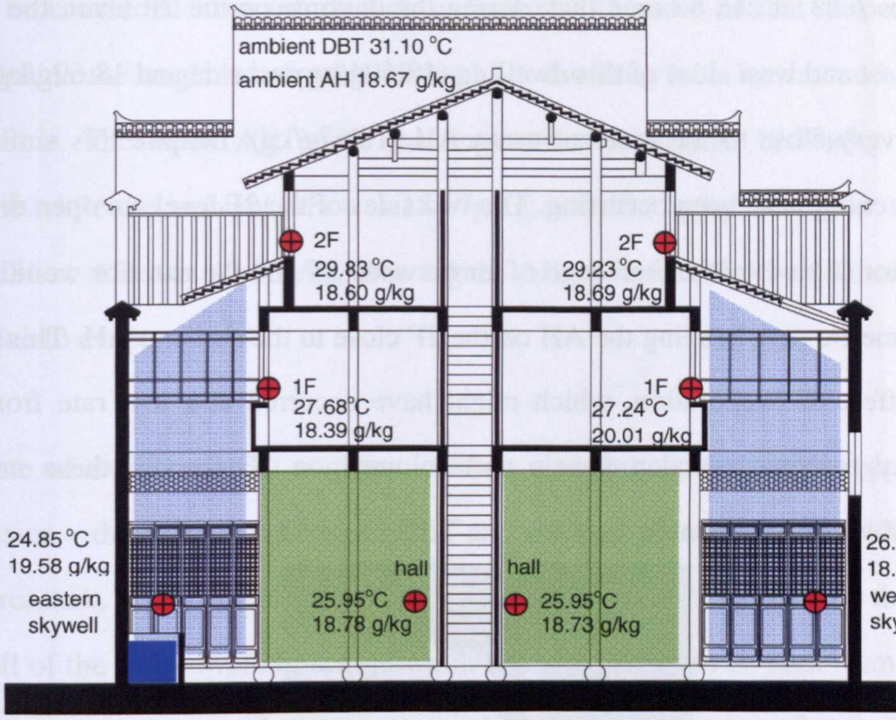


Figure 6. 23 Mean DBT and AH inside the Lufu dwelling during the daytime in the summer recording period

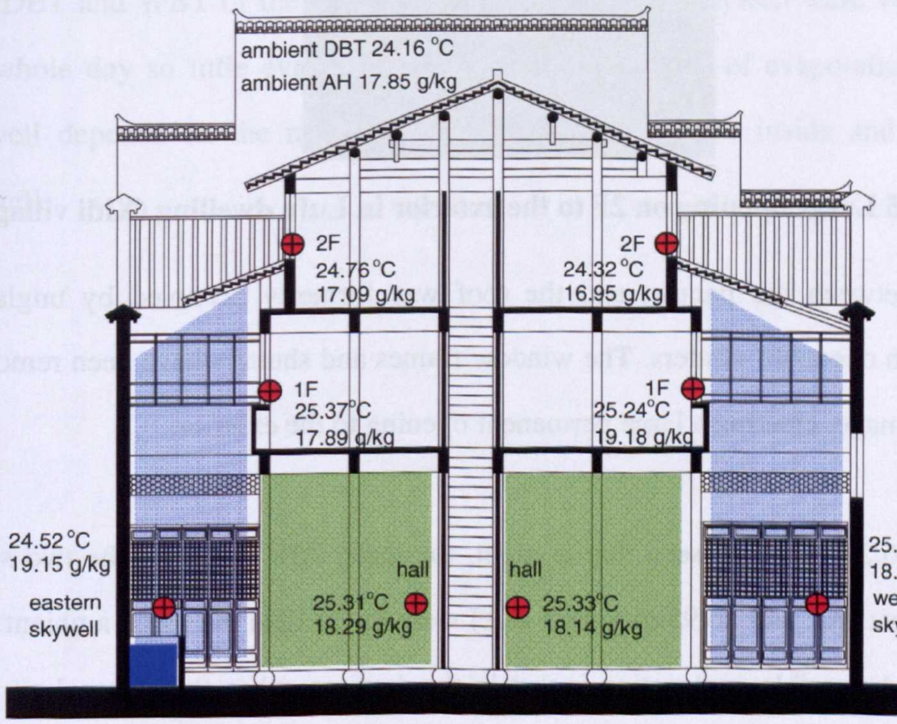


Figure 6. 24 Mean DBT and AH inside the Lufu dwelling (Xidi village) during the night time in the summer recording period

From figures 6.23, it can be seen that, during the daytime on the 2F level, the mean AH of the east and west sides of this dwelling (18.60g/kg east side and 18.69g/kg west side) were very close to the ambient mean AH (18.67g/kg). Despite this similarity, evaporation could have been occurring. The two sides of the 2F level are open directly to the exterior (figure 6.25). Exchange of air between 2F and the exterior would be at a high volumetric rate, keeping the AH on the 2F close to the ambient AH. This could mask the effect of evaporation, which might have occurred at a low rate from the sparingly hygroscopic wooden panels and columns on 2F (on 2F these are the predominant surface elements).

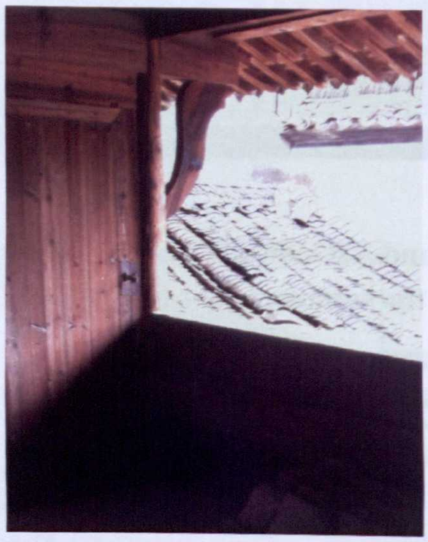


Figure 6. 25 Large opening on 2F to the exterior in Lufu dwelling (Xidi village)

The space between the parapet and the roof was formerly occupied by unglazed windows with openable shutters. The window frames and shutters have been removed following damage, creating a large permanent opening to the exterior.

From figure 6.24 it can be seen that at night, the mean AHs on 2F of the two sides (17.09g/kg east side and 16.95g/kg west side) were lower than the mean ambient AH (17.85g/kg). A possible explanation is that in the daytime, when the external air was less humid than at night (RH was low), the hygroscopic materials in the rooms released water vapour; in the night time, when the external air was humid (RH was high), the materials absorbed some water vapour from the air.

It can be concluded from information in figures 6.23 and 6.24 that evaporation took place inside the unglazed skywell of the Lufu dwelling both by day and also in the night time. The mean AH inside the unglazed skywell was 19.58g/kg during the daytime while the ambient AH was 18.67g/kg; and 19.15g/kg during the night while the ambient AH was 17.85g/kg. The higher AH values inside the unglazed skywell were due to evaporation.

The rate of evaporation at a given location is mainly influenced by the wet bulb depression – the difference between DBT and wet bulb air temperature (WBT) (Kwok and Grondzik, 2007). The DBT, WBT and AH of air inside and outside the unglazed skywell of the Lufu dwelling are shown in figure 6.26. It can be seen from this figure that the greatest degree of evaporative cooling would have taken place around 12:00 since the value of wet bulb depression of ambient air was greatest at this time of day while in the evenings and at night the values of wet bulb depression were very small. The DBT and WBT of the air inside the Lufu unglazed skywell were very close for the whole day so little evaporation could occur. The rate of evaporation inside the skywell depends on the rate of exchange between the air inside and outside the skywell.

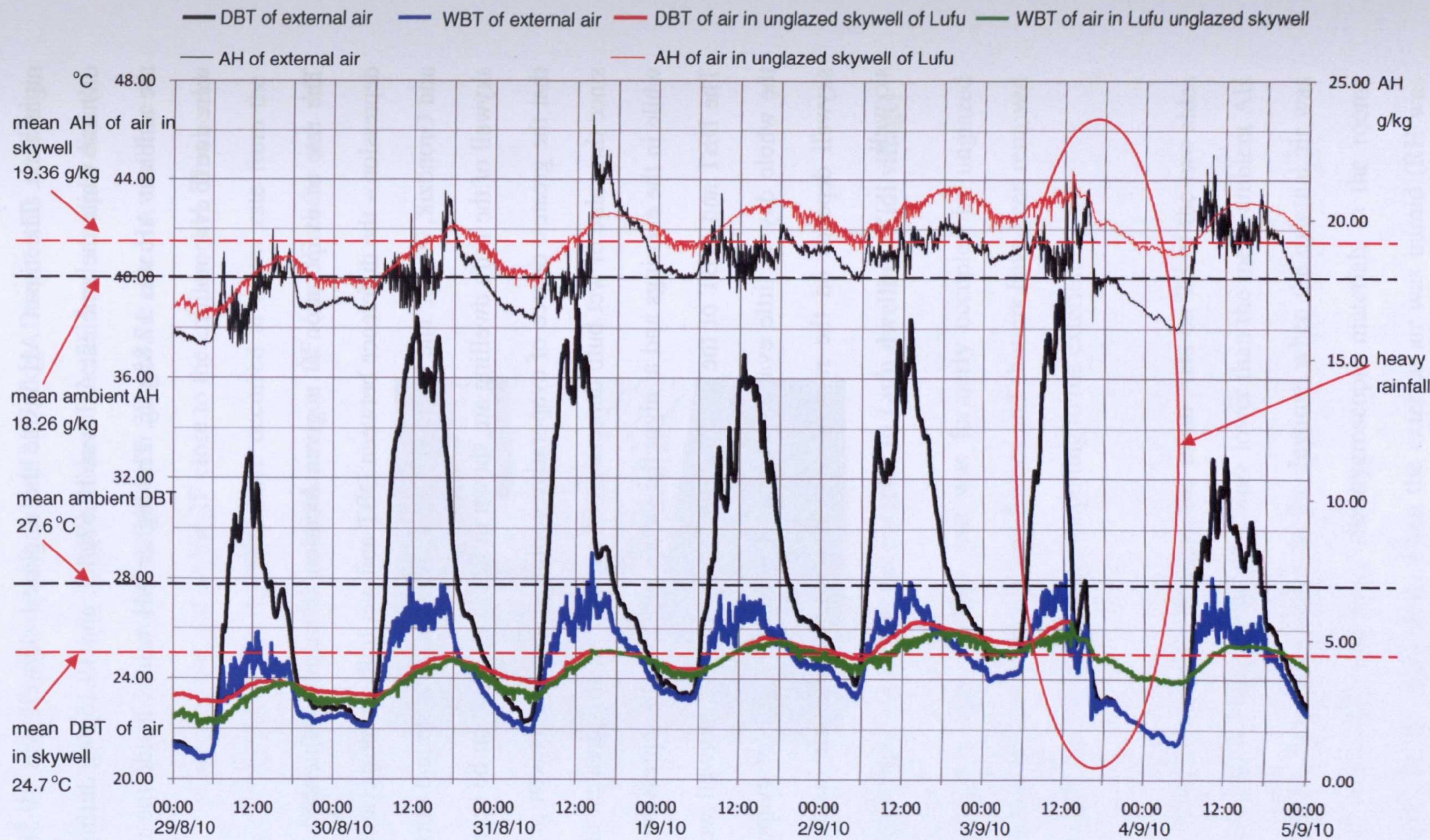


Figure 6. 26 DBT, WBT and AH of air inside and outside the unglazed skywell of the Lufu dwelling in summer recording period

All doors of the Lufu dwelling were normally kept open in the summer daytime and air could be exchanged freely between the skywell and the exterior. The ambient air with higher DBT and lower AH would be able to enter the skywell where the air had lower DBT and higher AH. Evaporation would then occur. The mixing of ambient and skywell air would increase DBT and reduce AH within the skywell; at the same time, evaporation would reduce DBT and increase AH. Ambient air entering the skywell displaces the existing skywell air, which is very humid and contains a large amount of latent heat. With a high rate of exchange of air between the interior and exterior of the skywell, the rate of evaporation inside the skywell would be high; with a low rate of exchange of air, evaporation would be greatly restricted due to the high RH.

In the daytime the RH and AH of external air are much lower and a little lower respectively than the equivalent values inside the skywell. It can be shown that, in the daytime an influx of hotter, drier ambient air can bring more heat into the skywell than is lost by the increased evaporation that follows. For example consider the DBT, WBT, RH and AH of air inside the skywell of the Dunren dwelling, the unglazed skywell of the Lufu dwelling and ambient air in the daytime. These are shown for a specimen date and time within the summer recording period in table 6.5.

Table 6. 5 DBT, WBT, RH and AH of air inside Dunren skywell, the unglazed Lufu skywell and in ambient air at 12:00 on 30th August 2010

	DBT (°C)	WBT(°C)	RH (%)	AH (g/kg)
ambient air	37.7	27	44.4	18.2
air inside the Dunren skywell	25.6	25.2	96.5	20.1
air inside the unglazed Lufu skywell	24.4	24.1	97.9	18.9

For change in temperature without change in phase

$$Q = m*C*\Delta T$$ where Q = heat energy, m = mass

C = specific heat capacity

ΔT = change in temperature

(for air, $C = 1.0 * 10^3 Jkg^{-1}k^{-1}$)

For change of phase without change in temperature

$$Q = m*L$$ where L = latent heat

(for water, specific latent heat of vaporisation = $2.4 * 10^3 KJkg^{-1}k^{-1}$)

Consider 1kg of hotter ambient air entering the skywell of the Dunren dwelling and displacing 1kg of cooler air out of the skywell. Calculate heat Q brought into skywell.

$$Q = 1kg * 10^3 Jkg^{-1}k^{-1} * (37.7°C - 25.6°C) = 12.1*10^3 J$$

The newly entered hotter air can hold more water vapour than the displaced air. Additional water can evaporate from water trough and skywell surfaces. For 1 kg air, the cooling effect Q is given by

$$Q = (20.1g - 18.2g)* 2400J\ g^{-1} = 4.6*10^3 J$$

Net heat increase in skywell from ingress of 1 kg air is $7.5*10^3$J. Applying the same procedure and assumptions, and carrying out equivalent calculations for the Lufu skywell, heat brought in by 1kg ambient air= $13.3*10^3$J, heat removed by evaporation of additional water in 1kg ambient = $1.7*10^3$J, net increase of heat energy in skywell exchange of 1kg air = $11.6*10^3$J.

As in the example shown above, when the rate of exchange of air between the skywell and the exterior is high; hotter, drier air from the exterior is able to replace cooler, more humid air at a high rate in relation to the volume of the skywell. The incoming hot air can hold more water vapour than the outgoing cooler, more humid air. This promotes evaporation within the skywell, which can remove a large amount of heat; however, the influx of higher temperature ambient air could bring a large amount of additional heat into the skywell: in instances such as the ones described above. For the two dwellings, this does not increase the DBT of air in the skywell markedly because of the high heat capacity of the building.

The values for temperature of ambient air are likely to be unrepresentatively high. Ambient air temperature was recorded by a data logger located on the roof of a building. Winds blowing into the skywells entered at ground level, where the air temperature is likely to have been several degrees cooler than the temperature on the roof, due to shading by nearby buildings (see section 6.6.1). (It would have been impractical to place the data logger on the ground due to pedestrian traffic.)

At night, with the doors closed the exchange of air between the interior and exterior of the unglazed skywell of Lufu dwelling would be greatly reduced. However, there is evidence that stack effect ventilation took place during the night (see section 6.5.1), which would enable evaporation to occur within the skywell. The night ventilation pattern of Lufu dwelling is shown in figure 6.27. The ambient air and the air inside the unglazed skywell were found to be almost saturated; however, when ambient air with lower DBT enters the skywell, the temperature of that air would be raised by the convection and radiation (from the construction materials inside the skywell) increasing the ability of the air inside the skywell to hold water vapour. This enables evaporation to occur.

During the night the difference in temperature between air inside and outside the skywell is small. Some heat is lost from the skywell by convection as cool ambient air enters the skywell and warm air inside the skywell exits. Much more heat is lost by evaporation, which can occur at night despite the lower ambient temperature. As the cool ambient air enters it is warmed by skywell air by convection, and warmed by the fabric of the building by radiation (the building retains heat acquired in the daytime).

This increases capacity to hold water vapour, which promotes evaporation within the skywell.

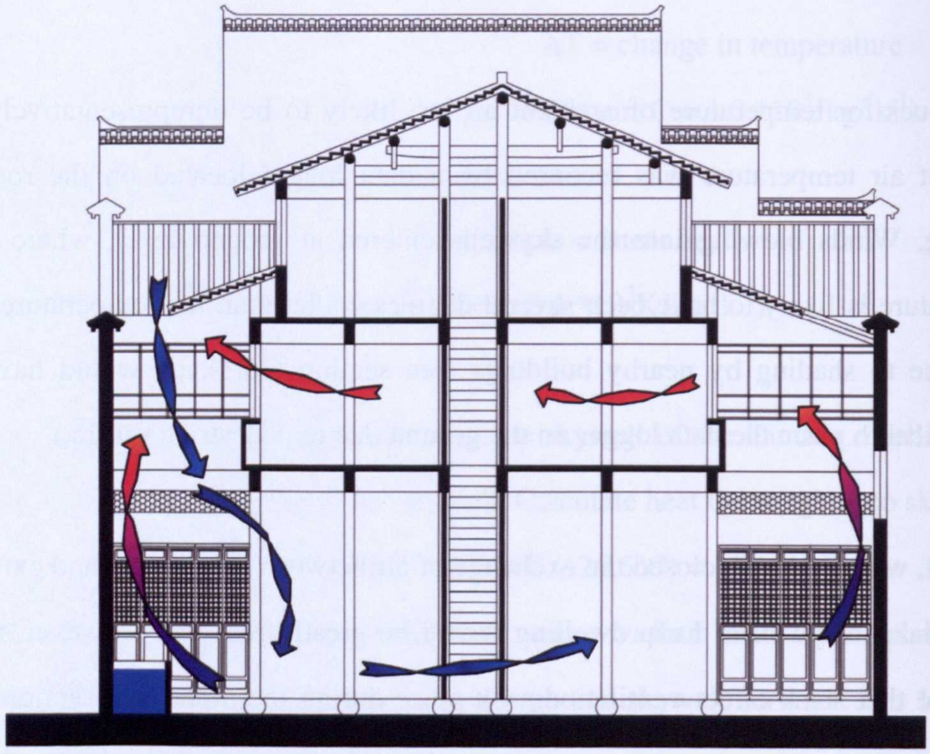


Figure 6. 27 Night air flow pattern in Lufu dwelling

To understand the effect of these processes, consider the DBT, WBT, RH and AH of air inside the skywell of the Dunren dwelling, the unglazed skywell of the Lufu dwelling and ambient air in the night time. These are shown for a specimen date and time within the summer recording period in table 6.6.

Table 6. 6 DBT, WBT, RH and AH of air inside Dunren skywell, the unglazed Lufu skywell and in ambient air at 4:00 on 31st August 2010

	DBT (°C)	WBT(°C)	RH (%)	AH (g/kg)
ambient air	22.4	22.2	98.40%	16.8
air inside the Dunren skywell	23.2	22.7	96.20%	17.2
air inside the unglazed Lufu skywell	24	23.5	96.20%	18.1

Consider 1kg of cooler ambient air entering the skywells of these dwellings and displacing 1kg of warmer air from the skywell. Using the same calculation prodedure as was employed previously for estimation of heat exchange in the daytime, it can be shown that at night, in the Dunren skywell, heat lost from skywell by convection as 1kg ambient air enters = $0.8*10^3$J, heat lost from skywell by evaporation into warmed ambient air = $0.96*10^3$J, net loss of heat energy in skywell by exchange of 1kg air = $1.8*10^3$J. Applying the same procedure to the Lufu skywell, heat lost from skywell by convection as 1kg ambient air enters = $1.6*10^3$J, heat lost from skywell by evaporation into warmed ambient air = $3.1*10^3$J, net loss of heat energy in skywell by exchange of 1kg air = $4.7*10^3$J.

In the summer measuring period, the mean AH in 1F under the glazed skywell of Lufu dwellings was the highest of the mean AH values obtained at the different loctions in the house (daytime 20.01g/kg, night time 19.18g/kg). The buoyancy force which drives the stack effect causes the air within a skywell to stratify, with warm layers at the top and cooler layers below. Because the western skywell of the Lufu dwelling is glazed, the ventilation in that area was poor. Hot air enriched in water vapour therefore accumulated beneath the glazing.

From figures 6.22 – 6.24 and figure 6.28, it can be seen that at all sampling times the AH of air inside the hall below the unglazed skywell was slightly above the ambient AH but lower than the AH of air in the skywell. Similar results were obtained in the other dwellings studied in Xidi and Zhifeng villages. The additional water vapour that account for the slightly higher AH in the hall than in ambient air may be supplied by hygroscopic construction materials (wooden columns, panels and floor material), or by the outward movement of humid air from the skywell. From comparison of humidity data obtained from the eastern and western skywells, it can be concluded that the main water sources for evaporation under the unglazed skywell were the water trough and the damp skywell wall not the other hygroscopic building materials.

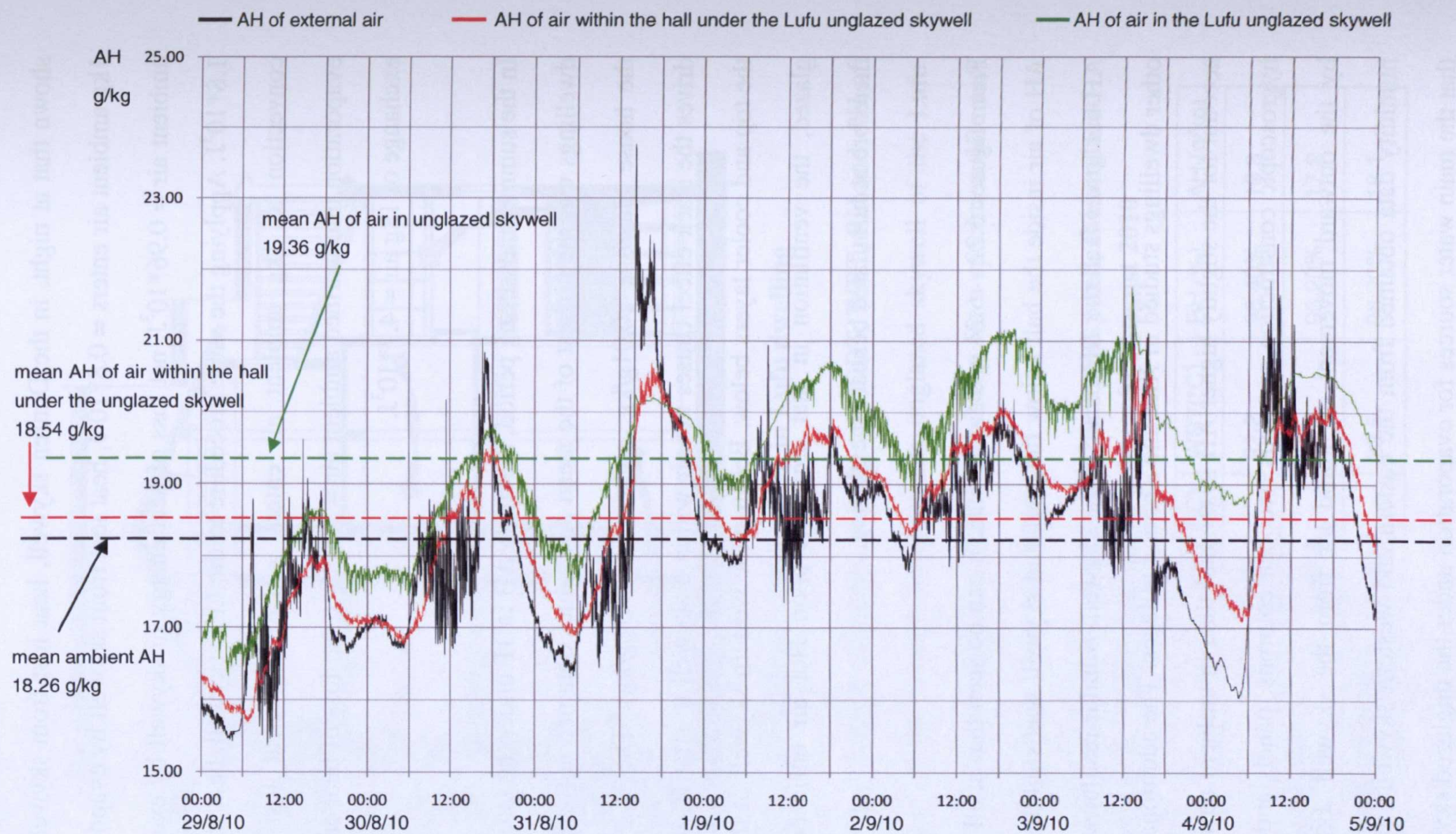


Figure 6. 28 Absolute humidity data within the unglazed skywell and its hall of Lufu dwelling (Xidi village) in summer recording period

Water for evaporation principally from wet skywell surfaces, and secondarily from water trough

The principal water sources for evaporation within the skwyells appear to be the water trough, the damp/wet inner surface of the skywell wall, and (in some skywells) the wet floor. It is likely that the wet surfaces make a larger contribution to evaporation since the area of the wet surfaces is much larger than the surface area of the water trough.

For example during the recording period in the Yingfu dwelling (Xidi village), evaporation was found to occur at a rate sufficient to influence temperature in the skywell (see figure 6.14) despite the water container being very small (see figure 4.10) and in spite of there being no skywell wall which could store water. This is because there is a large wet area on the skywell floor. In the skywell of the Yingfu dwelling, an area of the floor is given over to a traditional combined arrangement of potted plants interspersed with ornamental rocks (see figure 4.10). The plants do not appear to be intentionally watered; instead, they acquire water in the form of spray from waste water as residents discharge it into the skywell, and from rain. The rocks and the surfaces of the plants and pots add substantially to the surface area of the floor; they thus add to the capacity of surfaces within the skywell to retain water. In addition, the decorative rocks are covered in moss and algae, which can retain a considerable quantity of water per unit area of their growth. Thus, the surfaces within the skywell of the Yingfu dwelling can hold a great reserve of water for evaporation, which is able to increase the AH of the air within the skywell above the ambient value.

In Zhifeng village the AH inside the southern skywell of the Panxianxiong dwelling was markedly higher than the ambient AH, and higher than the AH in the eastern skywell of the Panmaotai dwelling (see figure 6.15). This is despite there being no water contained in the water trough (see figure 6.19). In the eastern skywell of the Panmaotai dwelling the sources of water for evaporation are a round ceramic water butt of traditional design (see figure 5.31) and the inner surface of the skywell wall which can acquire and retain rainwater. The southern skywell of the Panxianxiong dwelling can also acquire and retain rainwater at the inner surface of the skywell wall; but, in addition, the occupants of this building always pour their waste water into a small, rudimentary trough close to one edge of the skywell floor. Because of initial splashing as the water is thrown into the trough, and the perviousness of the gaps between the stone sheets, the troughs do not retain water; water that does not drain down the hole in the floor at the base of the trough wets the nearby walls and floor. The area of visibly wet wall and floor surface greatly exceeds the corresponding area observed in the eastern skywell of the Panmaotai dwelling.

6.7.3 Summary

From the above discussions, the following conclusions can be drawn:

1 Evaporation occurred in the skywells of dwellings of Xidi and Zhifeng villages to an extent sufficient to influence the surface and air temperature in the skywells.

2 The construction materials of Chinese vernacular dwellings (skywell wall, floor material, wooden column and panels) are likely to be hygroscopic.

3 The water for evaporation is mainly from the water trough and damp inner surface of the skywell wall.

4 The exchange of air between the skywell and the exterior of the building is important in determining the magnitude of evaporation inside the skywell.

6.8 Effect of internal heat gain

Heat gain from internal sources such as electrical appliances and the bodies of the occupants had a small effect on the thermal condition of the skywell dwellings. This is exemplified by consideration of the thermal environment of the dwellings studied in Xidi village. In the bedrooms of the Dunren dwelling and the Lufu dwelling a small early evening peak in temperature was observed every day at some time between 21:00 and 23:00. At these times, house occupants normally watch TV in the bedrooms after dinner. The bedroom location is conducive to relaxation and provides shelter from insects in the hot months. The increase in temperature was due to heat given off by electrical equipment and by the occupants. A similar temperature peak was observed in the Yingfu dwelling between 20:00 and 22:00 on 3rd September 2010. This room was occupied by the owner's adult daughter on her frequent visits.

A small peak in temperature was observed in the Lufu dwelling between 5:00 and 7:00 in the summer recording period. The owner likes to sleep with a fan running in summer to repel mosquitos; on waking, he turns the fan off, removing its cooling effect and causing a short-lived spike in temperature.

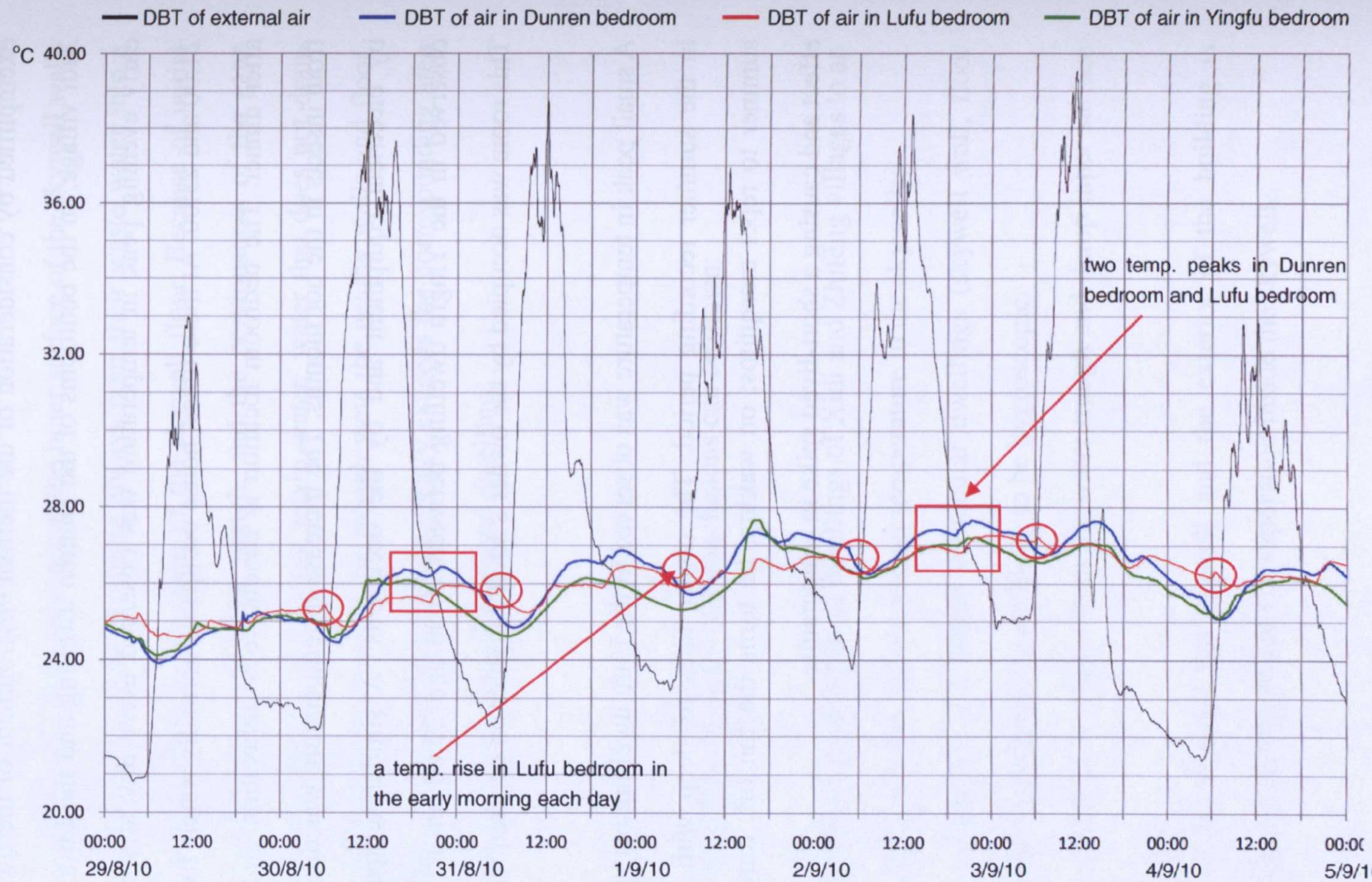


Figure 6. 29 DBT of ambient air and air inside the bedrooms of Dunren, Lufu and Yingfu dwellings (Xidi village) in summer recording period

6.9 Conclusion

The following questions were raised in section 6.3:

– Why were diurnal fluctuations in DBT inside the skwyell much narrower than those of the ambient air?

– Why was the mean DBT inside all skywells found to be 2.6 – 4.3°C lower in the summer recording period than the mean external DBT in Xidi and Zhifeng village while the mean DBT in the skywells in Yuyuan village was very close to the ambient mean?

These questions are answered below.

1 Chinese vernacular dwellings were found to have high heat capacities (the specific mass of all the dwelligngs studied was calculated to be over 400 kg/m^2). The massive structure of these dwellings is resistant to fluctuations in temperature.

2 Evidence was obtained that evaporative cooling had a substantial influence on the temperature in the skywells of dwellings in Xidi and Zhifeng villages. This further reduced the temperature fluctuation inside the skywell and was likely to have been the main reason that the mean DBTs inside the skywells in these villages were 2.6–4.3°C lower than the mean external DBT. In the skywells of dwellings studied in Yuyuan village the mean internal DBTs were very close to the mean external DBT; evidence was found that evaporation does not occur to an extent sufficient to influence skywell temperature in the courtyard-type skywells of Yuyuan.

3 Dwellings in Zhifeng and Xidi villages receive much less incident solar radiation through skywells than dwellings in Yuyuan village, due to the small size of the skywells in Zhifeng and Xidi. The large skywell in Yuyuan village amass more solar radiation than those in Zhifeng and Xidi, leading to higher skywell temperatures and

larger fluctuations in temperature in the Yuyuan dwellings.

4 Cross ventilation appear to have a substantial effect on temperature in the skywells. It appears to be disadvantagous for most of the daytime in summer since it brings additional heat into the skywell, raising the air temperature. This can be countered partially by ventilation, which increases evaporation in the skywell and removes a large amount of heat. Stack effect ventilation was found to occur at night; this form of ventilation was found to remove considerable amounts of heat from the skywell by convection and evaporation, thereby regenerating its heat storage capacity for the following day.

5 Radiant cooling is also likely to be important in recovering internal heat storage capacity. In skywell dwellings the skywell floor faces the sky directly, which could permit effective radiant cooling in cool summer nights.

7 THERMAL COMFORT IN SKYWELL DWELLINGS

7.1 Introduction

In the quantitative analysis of the daylighting and thermal performance of Chinese vernacular skywell dwellings described in chapters 5 and 6, it was shown that these vernacular dwellings are low-energy buildings. Examples of the efficient, low-energy functioning of these buildings are:

1 Satisfactory daylighting conditions for different visual tasks can be achieved in these skywell dwellings using natural light only

2 In summer the residents find the space within the skywells comfortable since these spaces were much cooler than the ambient air. Fans are rarely used.

However, it is only meaningful when residents can live in these traditional dwellings comfortably to carry out various activities. Numerical measures of temperature, humidity and air flow must be considered in relation to human experience.

In this chapter, thermal data recorded in the skywell dwellings in the summer measuring period are plotted into the psychrometric chart through the use of Ecotect software to evaluate the summer thermal comfort provided by the skywell dwellings. The distribution of thermal data points was examined in relation to the boundaries of thermal comfort zones. The measures taken to achieve winter thermal comfort are also presented since the residents found the skywell dwellings unacceptably cold in winter (see section 6.3). Research question 6 'How do residents achieve thermal comfort in summer and winter?' is answered.

The thermal comfort criteria are described first, and the factors of comfort and two comfort models are then introduced. Based on the psychrometric chart, the thermal comfort in the studied Chinese skywell dwellings is discussed. The actions residents have taken to maintain the thermal comfort are also described.

7.2 Thermal comfort criteria

Temperature / humidity data obtained at 1-minute intervals throughout the daytime (06:00-18.00) of the one-week summer recording period for the most occupied spaces are displayed on the psychrometric charts. On each chart the boundaries of the thermal comfort zone with still air assumed are shown with a black line. These boundaries and the underlying temperature / humidity contours were plotted using Ecotect. In setting the boundaries of thermal comfort zones Ecotect applies the following conditions

- To set boundaries of temperature comfort zone, use the expression $T_n = 17.6 + 0.31T_{o,m}$, where T_n = neutrality temperature and $T_{o,m}$ = mean outdoor temperature of the month.
- At 50% RH the width of the comfort zone is $T_n \pm 2°C$
- Upper and lower AH limits are 12 gkg^{-1} and 4 gkg^{-1} (from ASHRAE Standard 55-81)
- RH in thermal comfort zone must not exceed 90% (i.e. 90% RH contour of chart must be a boundary of the thermal comfort zone if zone is in contact with that contour)

In constructing the psychrometric charts residents were assumed to be sedentary, on the basis of observation of their general level of physical activity. During the summer recording period air speeds in the range <0.1 ms^{-1} - >2 ms^{-1} were observed. Having defined thermal comfort zones on the psychrometric charts in which still air was assumed, thermal comfort zones were also defined in which air movements affording natural ventilation were assumed to occur. On the basis of on-site measurements, air speed in skywells was taken to be 1 ms^{-1}, and those in halls and bedrooms were taken to be 0.2 ms^{-1}. This is because during the measurement on site it was observed that the air flow was weak in the hall but much higher in the skywell. The assumed air speed value is only for showing the effect of air movement on occupants' thermal comfort. On each of the psychrometric charts the boundaries of the thermal comfort zone with cross ventilation operating is shown with a red line.

7.3 Thermal comfort

7.3.1 Factors of comfort

Thermal comfort is highly subjective and varies with individuals. To be thermally comfortable one must not feel too hot or too cold; the amount of heat being produced by the body must be in balance with heat loss (Thomas, 2006). According to Szokolay (2008), the factors affect human's thermal comfort can be grouped into three sets:

Environmental	*Personal*	*Contributing factors*
Air temperature	Metabolic rate (activity)	Food and drink
Air movement	Clothing	Body shape
Humidity	State of health	Subcutaneous fat
Radiation	Acclimatization	Age and gender

From the above, the most influential factors are air temperature, air movement, relative humidity (RH), mean radiant temperature (MRT), occupants' level of activity, and amount of clothing worn by the occupants.

Air temperature is the principal environmental determinant of comfort, as it determines convective heat dissipation. Air movement accelerates convection and increases evaporation from the skin, thus producing a physiological cooling effect (Szokolay, 2008). According to Szokolay (2008), subjective reactions to air movement are:

<0.1 m/s	stuffy
To 0.2	unnoticeable
To 0.5	pleasant
To 1	subjects aware of movement
To 1.5	draughty
>1.5	annoying

The apparent cooling effect of air movement (dT) can be estimated using the equation mentioned in section 6.6.1 ($dT = 6\ V_e - 1.6\ V_e^{\ 2}$). Therefore the cooling effect for $1ms^{-1}$ air speed can be calculated as: $dT = 6 * (1 - 0.2) - 1.6 *(1 - 0.2)^2 = 3.8$ K.

For comfort the RH between 30 – 65% do not have much effect, but high humidities restrict evaporation from the skin and in respiration, and thus hinder the dissipation mechanism; very low humidities lead to drying out of the mouth, throat and skin, and thus cause discomfort (Thomas, 2006). For example, within the skywell dwellings studied in the three villages the RH recorded in the summer measuring period were very high (most of the values were over 80%). This high humidity can create great discomfort. Under these conditions the main relief for residents comes from the movement of air across the skin to increase the rate of evaporative cooling. Therefore, there is a great need for natural ventilation in the very humid climates.

Radiation exchange depends on the temperature of surrounding surfaces, measured by mean radiant temperature (MRT). The effect upon comfort of MRT depends on clothing. In warm climates in which light clothing is worn, MRT is about twice as important as the DBT. In cooler climates in which heavier clothing is worn, MRT has about the same influence as the DBT (Szokolay, 2008). People prefer low MRT in summer and high MRT in winter.

Metabolic rate is a function of activity level. Met as its unit corresponds to 58.2 W/m2 of body surface area. The human body maintains a basic minimum rate of heat production at about 60 Watts during sleep and about 70-120 Watts when awake but sedentary (Thomas, 2006).

Clothing is thermal insulation for the body. Generally, the thicker a garment is the greater insulating abilities it has. The amount of clothing is measured against a standard amount that is roughly equivalent to a typical business suit, shirt and undergarments. This standard amount of insulation required to keep a resting person warm in a windless room at 21.1°C is equal to one clo, which is 6.45 $Wm^{-2}K^{-1}$ (Szokolay, 2008).

7.3.2 Approaches to the prediction of thermal comfort

The two main thermal comfort models that are used for the prediction of comfort are the Fanger model and the adaptive comfort model. The Fanger model is a heat balance model derived from laboratory studies of heat exchange between the body and the environment (Fanger, 1972). The adaptive comfort model is based on results obtained in field studies, and incorporates recognition of climatic context and occupants' expectations (de Dear and Brager, 1998).

In constructing the Fanger model participants were exposed to different thermal conditions of temperatures, humidity, MRT and air speed in a closed climate chamber. Personal factors of activity level and clothing were also varied. Participants were asked to rate the acceptability of different conditions by using the seven-point form of a thermal sensation scale which is from -3 (cold) to +3(hot) with zero representing a neutral point. Fanger used the comfort data to develop the Predicted Mean Vote (PMV) equation, which can be used to predict the thermal comfort of existing and proposed buildings.

However, based on field studies in hundreds of real buildings Humphreys (1978) found that the range of temperatures that are considered comfortable varies considerably worldwide. This tends to undermine predictions made using PMV. Numerous authors have found marked discrepancies between actual thermal comfort sensation of occupants and comfort values predicted using the PMV (Schiller, 1990; Croome et al., 1992; Busch, 1992, Humphreys, 1994; Ye et al., 2006; Goto et al., 2007).

The PMV model is based on data obtained from climate chambers in steady-state conditions but thermal environments are experienced in a dynamic interaction between occupancy, building and climate (Hensen, 1990). The adaptive comfort model was proposed in order to reflect this. "Comfort is the result of the dynamic interaction between people and buildings in a particular social context, not a steady-state fulfilment of the physiological conditions for thermal comfort." (Nicol and Roaf, 2005) The adaptive model emphasizes the important role of building occupants securing their own thermal comfort by making adjustments and adaptions (Shove, 2003).

In surveys of thermal comfort in buildings, numerous authors have found that the proportion of occupants of a building who are satisfied with their thermal conditions is greatly increased when various means are provided for them to control their local environment (Humpherys and Nicol, 2000). Building occupants have also been shown to be more tolerant of conditions and more willing to forgive occasional periods of poor performance of buildings when means of control were available to them (Leaman and Bordass, 2000). In the adaptive model, comfort temperatures are not fixed as in the Fanger model; in the adaptive model a wider range of indoor temperatures can be considered as comfortable depending on the season and location. Using occupant ratings of temperature comfort in different buildings, Humphreys (1978) produced the following emperical equation and associated procedure for calculating the indoor comfort temperature of a free running building from outdoor monthly mean temperature:

$T_n = 11.9 + 0.534\ T_{o.m}$ where Tn = neutral temperature

$T_{o.m}$ = mean outdoor temperature of the month

The temperature limits of the comfort zone can be taken relative to the above Tn as from (Tn – 2) °C to (Tn + 2) °C. A refined form of Humphrey's equation produced by Auliciems (1981) was used in the Ecotect analysis of thermal comfort in the dwellings considered in the present study. This refined equation is as follows.

$T_n = 17.6 + 0.31\ T_{o.m}$

In the present study the adaptive comfort model rather than the Fanger model was used for evaluating the thermal comfort in Chinese vernacular dwellings. The reasons for doing so were as follows:

1 The PMV model is based on data from artificial climate chambers. Such data lack contextual factors which have been shown to be important in determerming thermal comfort, and which are considered in the adaptive model (factors such as building location, climate, and the attitude and experience of building occupants). Chinese vernacular skywell dwellings are all free-running buildings that have been occupied for hundreds of years. Traditions and expectations that influence residents' experience of these buildings have arisen and solidified in this time.

2 In the PMV model, occupants are only considered as passive recipients of thermal stimuli presented by the artificial climate (de Dear, 2004), while in the adaptive model, occupants interact with and adjust to their environment (de Dear and Brager, 1998). In the Chinese vernacular dwellings considered in the present study, residents were seen to use various measures to make themselves comfortable, such as changing their clothes, moving to shaded spaces, opening doors, and using small fans in summer.

3 As noted previously, building occupants are more tolerant of conditions if they have more opportunities for control open to them (Leaman and Bordass, 2000). As stated in 2 above, residents of the vernacular skywell dwellings investigated were found to take action to improve thermal conditions for themselves. These measures widen the range of comfort temperatures in their houses, and were taken into account in the analysis below.

7.4 Thermal comfort in the Chinese skywell dwellings studied

During the summer field studies, it was observed that the residents of the three dwellings studied in Xidi village spend most of their daytime in the hall and skywell since they run souvenir selling businesses within their houses. Most residents of the houses studied in Zhifeng village and Yuyuan village were absent from the skywell dwellings for most of the daytime, except the old and children. In Zhifeng, the children and the elderly prefer to stay in the yard, hall and skywell during the daytime while in Yuyuan village people in these age ranges prefer to occupy the veranda and bedroom in the daytime.

The categories and main activities of occupants studied in most occupied space of the skywell dwellings in daytime, and the temperature comfort zone in the summer measuring period that derived from the adaptive comfort model are shown in table 7.1. The daytime thermal data of most occupied space in the skywell dwellings of the three villages recorded in the summer measuring period are then plotted into the psychrometric chart through the use of Ecotect software to evaluate the summer thermal comfort provided by the skywell dwellings.

Table 7. 1 Occupant categories and occupant activities in most occupied spaces of skywell dwellings in daytime in the three villages studied, and estimated temperature comfort zone

village		occupants	most occupied space in a skywell dwelling	activities	temperature comfort zone in summer measuring period
Xidi village	past	the old, women and children (adult males would engage in business outside the village)	hall and skywell	minor household tasks, craft work, reading, writing, chatting, playing, resting	24.0°C – 28.0°C
	present	whole family (except children aged 13+) who attend school in city nearby, and some adults who work in the city)	hall and skywell	selling souvenirs, reading, writing, playing, resting, chatting	
Zhifeng village	past	the old, children (whole family engaged in agricultural work in nearby fields)	yard, hall and skywell	minor household tasks, craft work, resting, chatting	24.2°C – 28.2°C
	present	the old , children (some members of family do agricultural work in fields, some work in the city; children aged 13+ study in the city)	yard, hall and skywell	minor household tasks, resting, chatting	
Yuyuan village	past	the old, children (other members of family engage in trade and run restaurants and shops elsewhere in village)	hall and veranda	minor household tasks, craft work, reading, writing, chatting, playing, resting	24.3°C – 28.3°C
	present	the old, children (adult members of family do agricultural work in fields/ work in city/ run restaurants and shops in village, children aged 13+ study in the city)	veranda and bedroom	minor household tasks, craft work, reading, writing, chatting, playing, resting	

Most occupied space indicates the part of the house with the largest notional score of number of people present/length of time present. It was found that one particular part of the houses studied on each of the three villages was occupied more than others at any time of day, so consideration of the most occupied space is of value in assessing the thermal functioning of the dwellings – at any time, the most occupied space is likely to be a distinct centre of occupancy.

Figures 7.1-7.6 are psychrometric charts created for the most occupied spaces of each of the dwellings studied, with the following exceptions and qualifications. Charts were constructed for: the skywell and halls of houses in Xidi and Zhifeng villages (temperature and humidity data were not recorded for the yards of skywell buildings of Zhifeng, and hence are not plotted on charts); for the bedrooms of the houses in Yuyuan village; and for the skywells in the houses in Yuyuan village as surrogate locations for the nearby verandas, where data were not recorded.

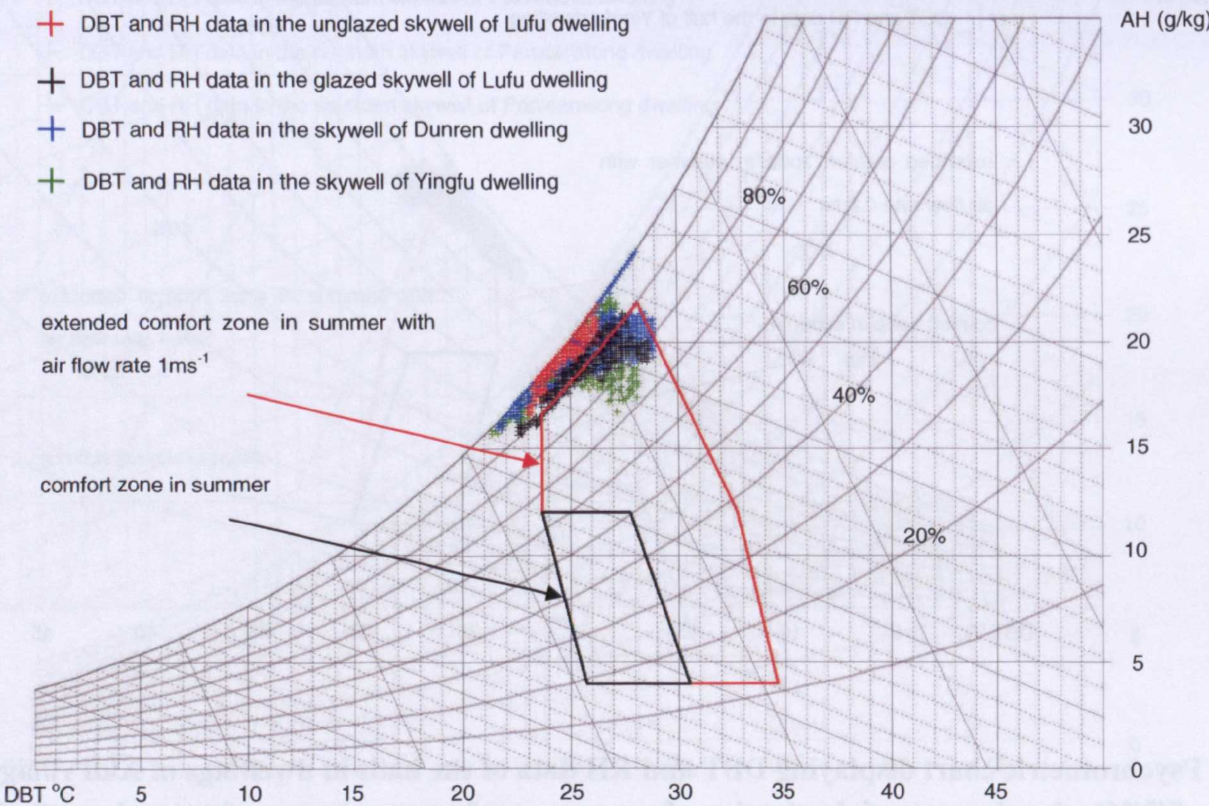


Figure 7. 1 Psychrometric chart displaying DBT and RH data of the skywells in dwellings of Xidi village in summer measuring period (29/8/10 – 5/9/10), showing potential extension of summer comfort zone by use of natural ventilation with air flow rate 1ms^{-1}

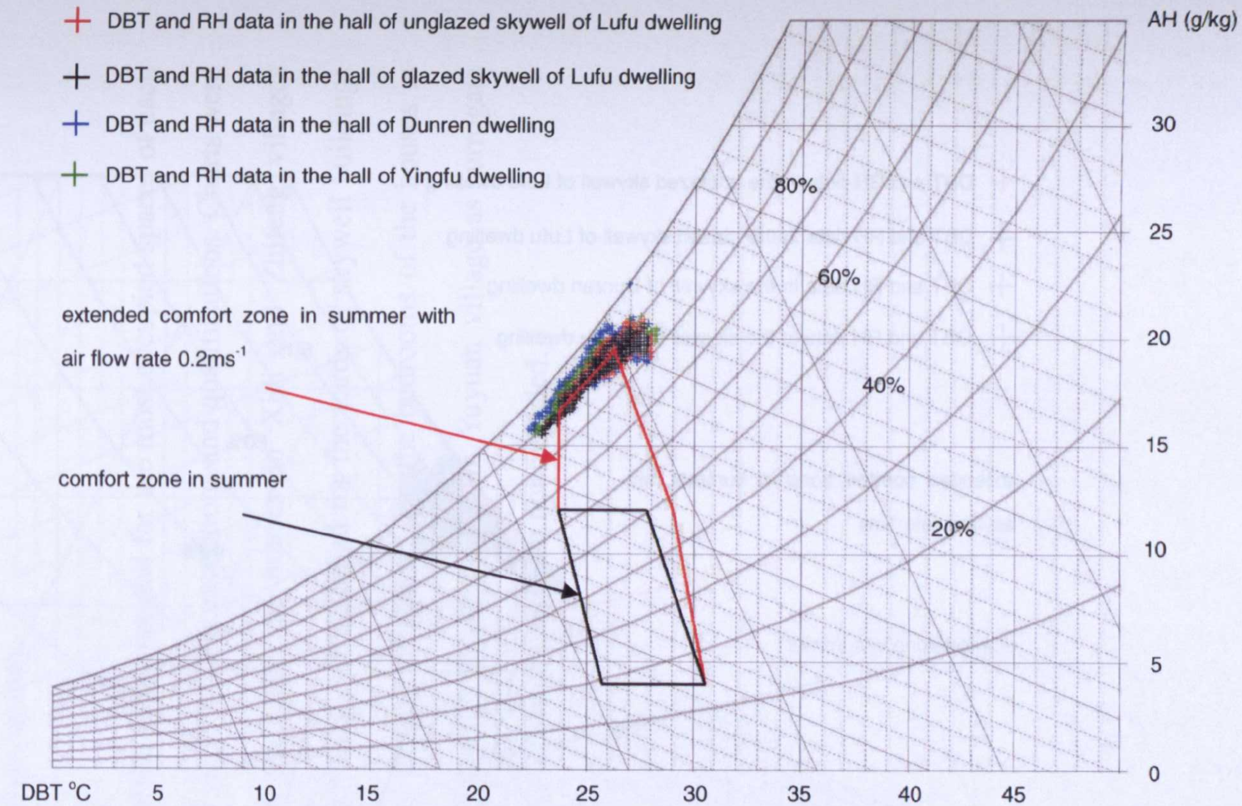


Figure 7. 2 Psychrometric chart displaying DBT and RH data of the halls in dwellings of Xidi village in summer measuring period (29/8/10 – 5/9/10), showing potential extension of summer comfort zone by use of natural ventilation with air flow rate 0.2ms^{-1}

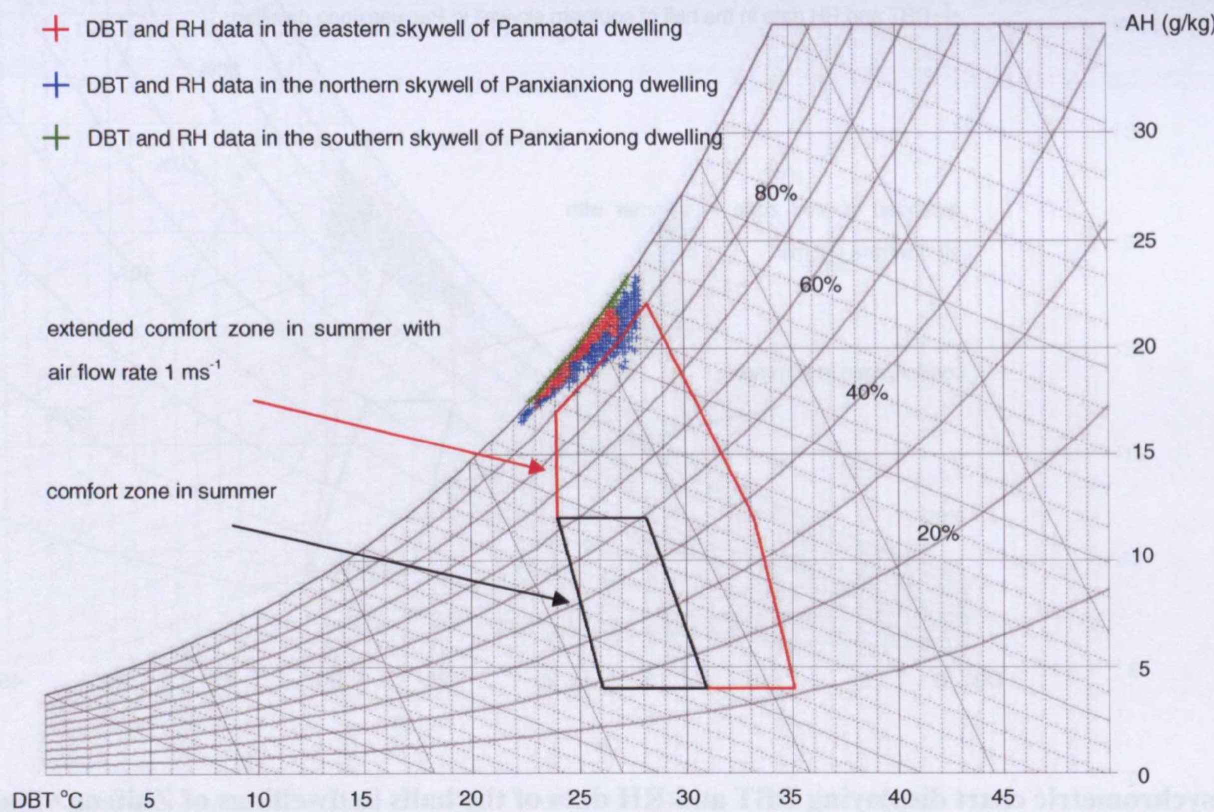


Figure 7. 3 Psychrometric chart displaying DBT and RH data of the skywells in dwellings of Zhifeng village in summer measuring period (29/8/10 – 5/9/10), showing potential extension of summer comfort zone by use of natural ventilation with air flow rate 1ms^{-1}

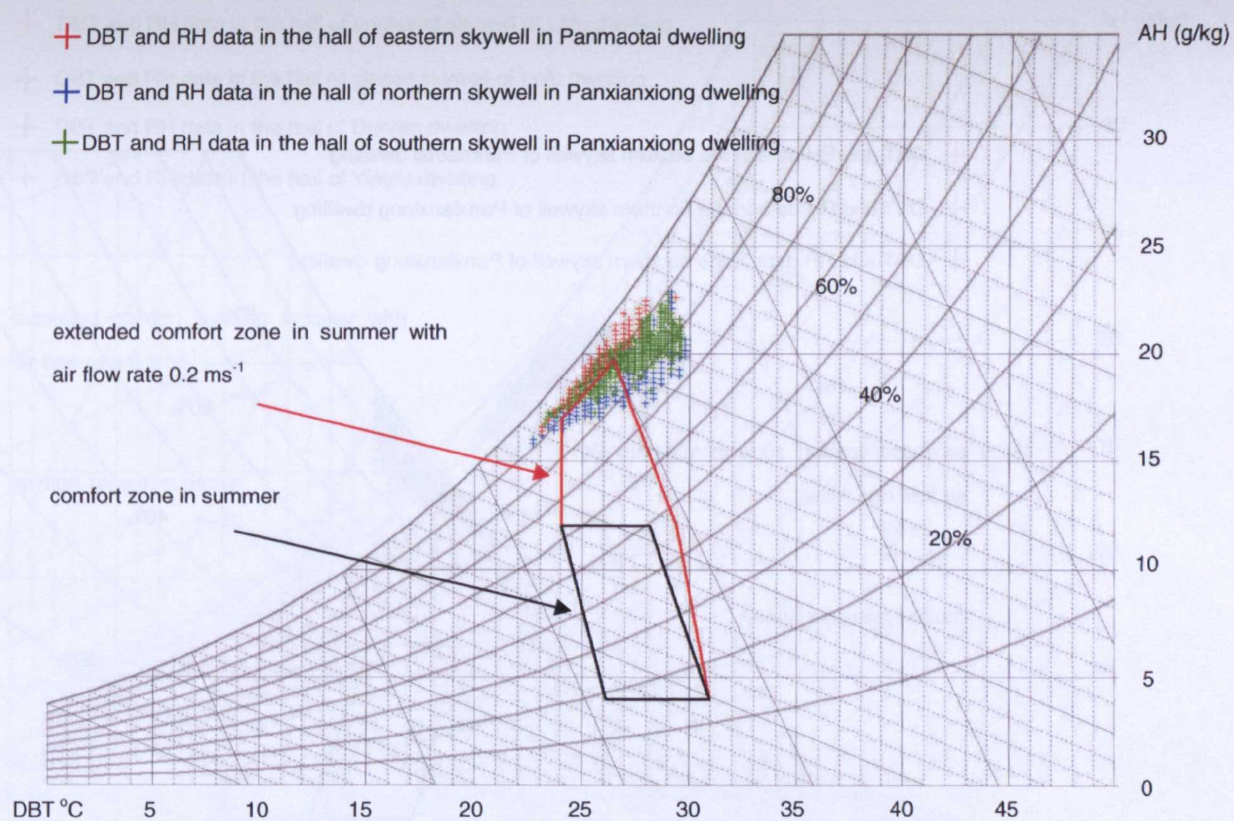


Figure 7. 4 Psychrometric chart displaying DBT and RH data of the halls in dwellings of Zhifeng village in summer measuring period (29/8/10 – 5/9/10), showing potential extension of summer comfort zone by use of natural ventilation with air flow rate 0.2 ms^{-1}

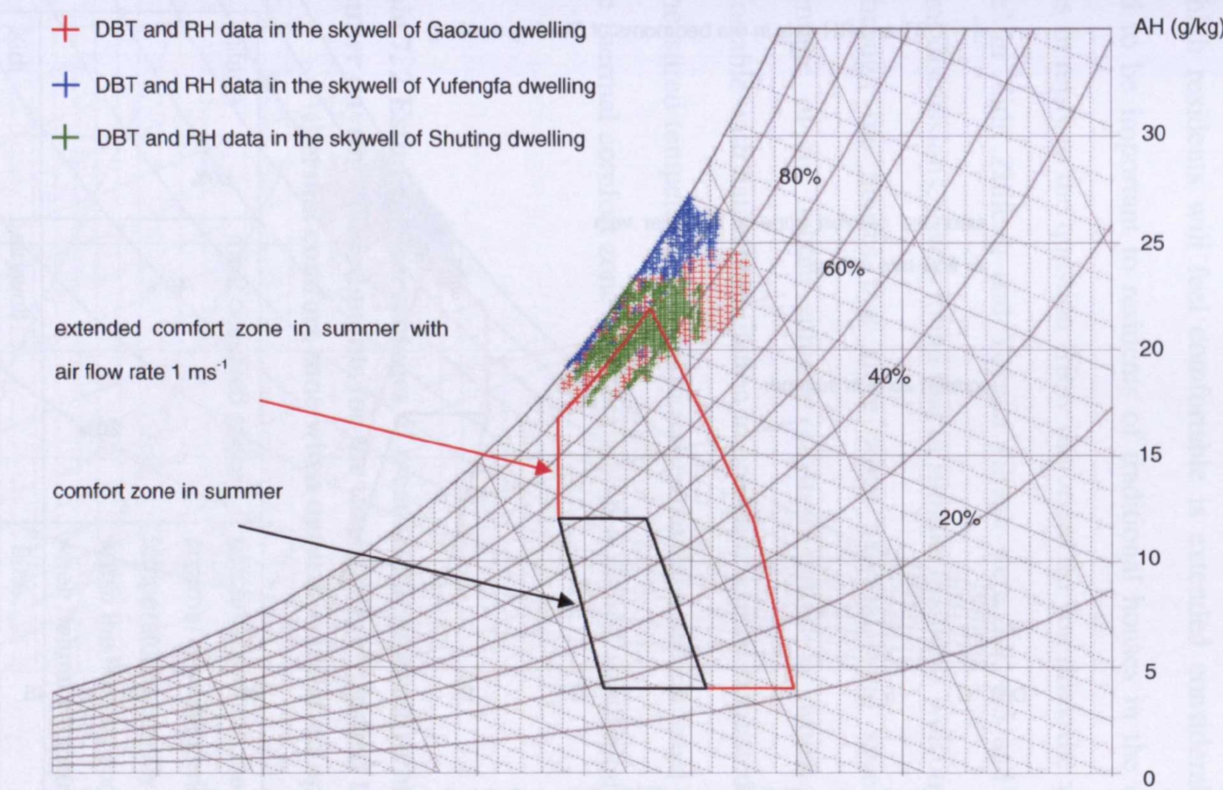


Figure 7. 5 Psychrometric chart displaying DBT and RH data of the skywells in dwellings of Yuyuan village in summer measuring period (29/8/10 – 5/9/10), showing potential extension of summer comfort zone by use of natural ventilation with air flow rate 1 ms^{-1}

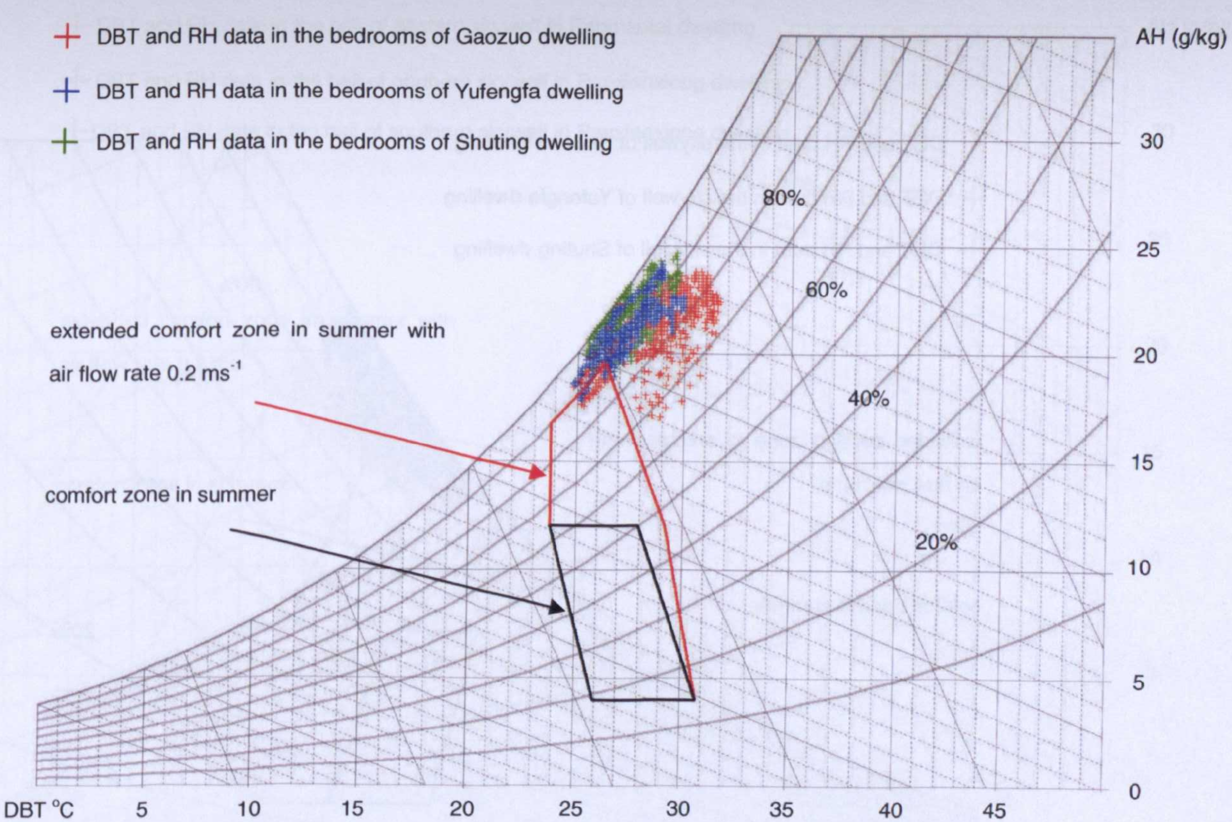


Figure 7. 6 Psychrometric chart displaying DBT and RH data of the bedrooms in dwellings of Yuyuan village in summer measuring period (29/8/10 – 5/9/10), showing potential extension of summer comfort zone by use of natural ventilation with air flow rate 0.2 ms^{-1}

In figures 7.1 – 7.6, it can be seen that all the temperature/humidity data points fell outside the still air comfort zones. With the provision of natural ventilation, the area of the comfort zone is enlarged twofold or threefold and thus, the duration of the period in which residents will feel comfortable is extended considerably. Ventilation was found to be important to residents of traditional houses in the questionnaire. Mean scores in reply to the question 'How important do you think the ventilation is in your house' in Xidi, Zhifeng and Yuyuan village were 4.9, 4.5 and 4.7 respectively. In general discussions, it was found that in summer residents welcomed the rapid flow of air through the houses that arose when external wind speeds were high. The percentage of the whole summer daytime period in which residents will feel comfortable with natural ventilation in operation can be estimated as the proportion of the measured temperature/humidity data points that are enclosed within the boundary of the thermal comfort zone that obtains when natural ventilation is considered (table 7.2).

Table 7. 2 Estimated percentages of measured temperature/humidity data from summer daytime period points for the three villages studied that fall within the thermal comfort zone when natural ventilation operates

village	most occupied space	percentage of the measured summer daytime period in which temperature/humidity data points fall within the thermal comfort zone when natural ventilation is applied
Xidi	skywell	50%
	hall	25%
Zhifeng	skywell	15%
	hall	30%
Yuyuan	veranda (data in skywell used)	25%
	bedroom	10%

The results displayed in table 7.2 are at variance with the results obtained in response to the question 'How satisfied were you with the comfort in your house in summer' which was put to the residents of skywell houses in the three villages in the questionnaire (see appendix A).

While it would be expected from the results in table 7.2 that a high proportion of village residents would be dissatisfied with the thermal environment in their most occupied spaces, the mean scores for whole-house thermal satisfaction in Xidi, Zhifeng and Yuyuan villages were 4.4, 4.0 and 3.4 respectively. A very high proportion of air temperature readings obtained in the most occupied spaces of houses in Xidi and Zhifeng villages were within the temperature comfort zone that applied when natural ventilation was assumed to be operating, while in Yuyuan village a lower but still very high proportion of temperature readings (about 70%) were within the temperature comfort zone. On the other hand, for most of the dwellings, a large majority of the temperature/humidity data points fell outside the ≤ 90% RH boundary of the thermal comfort zone. It is likely that, through lifetime acclimatization, the inhabitants of the villages are more tolerant of high humidities than the ≤ 90% RH boundary allows, leading to the underestimation in table 7.2 of the thermal acceptability of the most occupied spaces in the dwellings. In addition, residents of the three villages were seen to take steps to improve their thermal comfort during the summer recording period; this would further enlarge the range of thermal conditions in which the residents feel comfortable, and the proportion of time in summer in which they do so.

Although the degree of superimposition of temperature/humidity data upon thermal comfort zones failed to reflect the residents' satisfaction with the thermal performance of the most occupied spaces, the higher proportion of temperature data in Yuyuan that fell outside the temperature comfort zone than in the other two villages may be related to the lower score for whole-house summer thermal comfort reported by residents of traditional houses in Yuyuan than by residents of traditional houses in the other two villages.

In the summer daytime, residents of the three villages generally kept all the external doors of their houses open to allow the maximum air movement. Bedroom doors and windows in dwellings of Xidi and Zhifeng village were kept closed for most of the daytime – and in the case of Xidi village, often locked. The reasons for closure are that these bedrooms are rarely used in the daytime, and the residents are concerned for their privacy and safety (from time to time, a large numbers of travellers arrive by bus to visit the vernacular dwellings in Xidi village and – in many cases – to buy souvernirs). However, in Yuyuan village the doors and windows are kept open through most of the summer daytime since the bedrooms are more frequently used by residents and the establishment of a substantial flow of air inside the room for ventilation is very desirable.

Although in Xidi and Zhifeng village the most occupied spaces in summer were found to be the skywell and hall, residents were found to stay neither directly under the skywell, where the air was very humid, nor at the back of the hall, where illumination was poor. They were found to prefer to stay in the transitional space between the skywell and the hall (which is the edge of the utility area next to the hall area). In Yuyuan village, the veranda was found to be the most occupied space in the dwellings studied. As noted in figure 5.32, residents of the Gaozuo dwelling appear to attach more importance to securing a lower illuminance level on hot summer days than to finding shade. At the same time, they benefit from the higher air movement since this veranda space locates on the main axes of air flow between the inlet and outlet to the buildings (see figure D.8 in appendix D).

Figure 5.28 shows a desk that has been placed near a skywell of the Lufu dwelling in Xidi village to obtain better lighting conditions. The desk is not placed in a central position in the hall but along a line between the skywell and one of the doorways that connect the eastern and western skywells, thus ensuring exposure to more rapid air flow than would be obtained in a central location (figure 7.7).

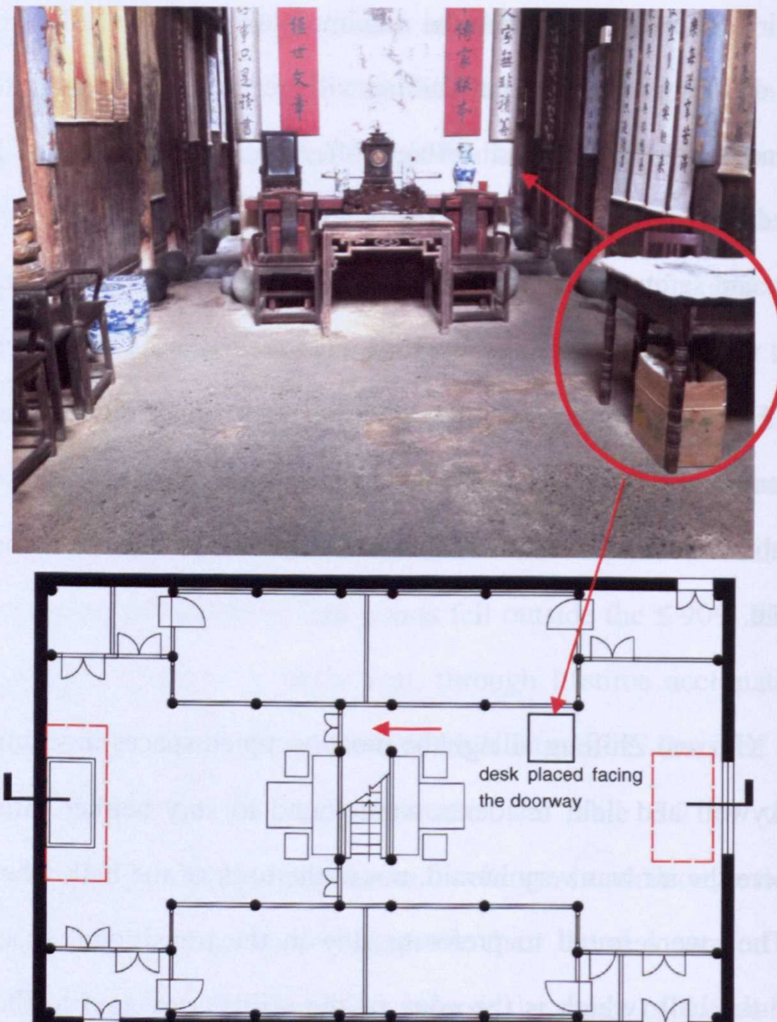


Figure 7. 7 Desk placed facing a doorway in direct path of air movement to enable a resident seated at desk to benefit from more rapid air movement

A large manual fan of traditional design is suspended from a beam in the eastern skywell of the Lufu dwelling. The fan may be a century old, or older. In the past a servant would have agitated the fan by pulling a string in order to create a breeze when wind-driven air movement through the house was insufficient (figure 7.8).

Figure 7. 8 An old manual fan in eastern skywell of Lufu dwelling

People in the three villages wear lighter clothes in summer. Shorts and short-sleeved shirts would give only about 0.5 clo (figure 7.9). In the Yingfu dwelling of Xidi village, the occupants use a piece of cloth to cover the skywell while the sunlight is intense to eliminate both glare (see figure 5.30) and the strong direct sunlight which could raise the MRT inside the skywell (figure 7.10).

Figure 7. 9 A resident with light clothes in the skywell of Yingfu dwelling (Xidi village) without using the cloth to cover the skywell in a summer day

Figure 7. 10 The skywell of Yingfu dwelling (Xidi village) covered by a piece of cloth on a summer day

7.5 Achieving thermal comfort in winter

As discussed in section 6.3, it was concluded that the design of Chinese vernacular skywell dwellings is mainly intended to counteract excessive summer heat than uncomfortable winter cold. Although the hills shield the village from cold winter winds, and all three villages can receive sufficient sunlight in winter, the compact layout of the dwellings in the three villages and narrow skywells in Xidi and Zhifeng villages restrict the amount of sunlight penetrating into the skywell dwellings considerably, which is beneficial in summer but not in winter; and there is a large amount of heat loss through the skywell which is open to the ambient air directly. Again, this is beneficial in summer but presents a problem in winter.

Thermal data from the skywell dwellings of the three villages in winter were not plotted on psychrometric charts since it was apparent from questionnaire and thermal recording data that the skywell dwellings were unacceptably cold (see figures 6.5 and 6.6). It is therefore necessary for villagers to take action to maintain the thermal comfort. Residents of the villages achieved thermal comfort in winter by wearing thick clothing, using heating devices, seeking exposure to the sun, and sleeping in traditional canopy beds. This is the reason why people in the three villages generally felt cold in winter but not severely so.

7.5.1 Thick clothing

Figure 7. 11 Residents of Gaozuo dwelling (Yuyuan village) wearing thick clothes in winter

In the villages studied, people normally wear thick clothes such as down garments in winter. This type of clothing would give about 3 clo, which means the conductance of its thermal insulation is 2.15 W/ $m^2 \cdot K$. This is sufficient to reduce heat loss considerably and to keep a person warm in winter in local conditions.

7.5.2 Heating devices

Many kinds of stove are used for warmth in the villages. The heating material is charcoal that has not been used up after cooking. The charcoal is placed in different kinds of stove that people can sit in (figure 7.12), sit on (figure 7.13 a) or move around (figure 7.13 a, b and c). Large stoves are occasionally moved within the house according to the need. Smaller stoves are moved within and outside the house, and are moved more frequently. To slow the loss of heat from the charcoal the stove is covered with a blanket (figure 7.14). At night before sleeping, the charcoal is extinguished to prevent fire and reduce the risk of carbon monoxide poisoning; hot water bottles are sometimes used to provide warmth in bed.

Figure 7. 12 Stoves for sitting in, found in Xidi and Zhifeng villages

a b c

Figure 7. 13 Stove for sitting on and moving around, found in Xidi and Zhifeng(a) and for moving around only found in Yuyuan(b and c)

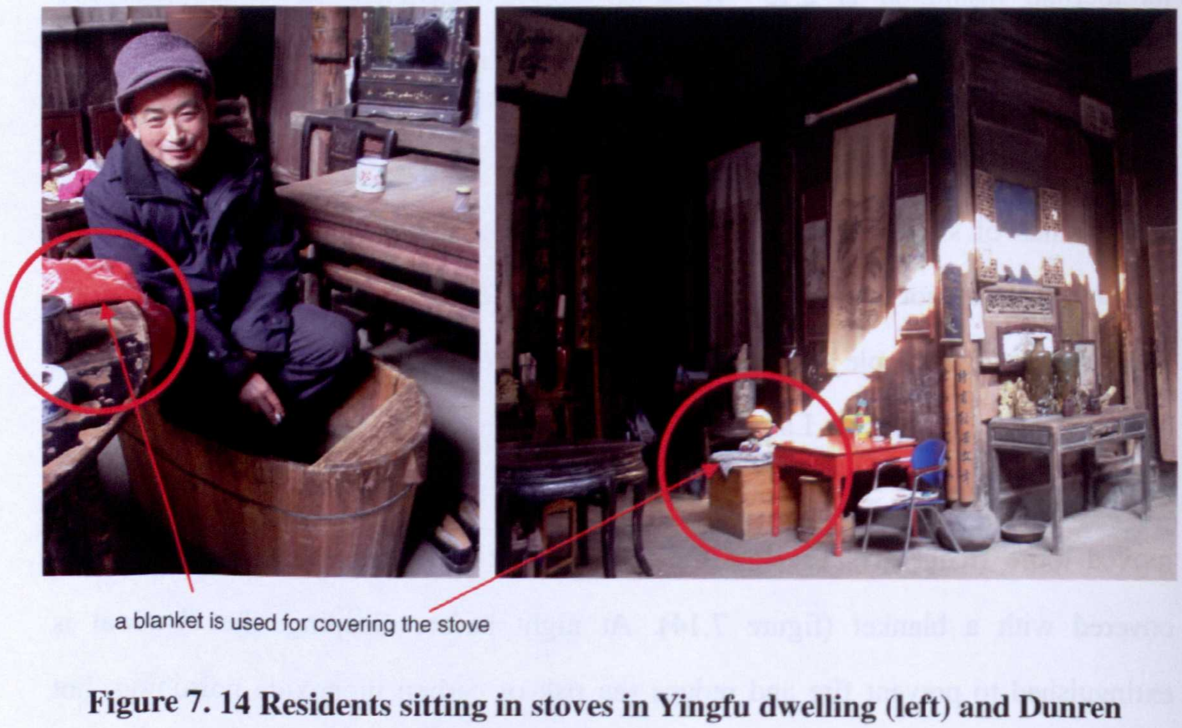


Figure 7. 14 Residents sitting in stoves in Yingfu dwelling (left) and Dunren dwelling (right) in Xidi village

7.5.3 Exposure to the sun

In cold winters residents seek to obtain warmth from direct sunlight, because the direct sunlight raises the mean radiant temperature (MRT).

Figure 7. 15 Resident of the Dunren dwelling (Xidi village) making the most of available sunlight in winter

Figure 7. 16 An elder in Yuyuangfa dwelling (Yuyuan village) sitting in sunlight in winter

7.5.4 Canopy beds

Traditional canopy beds are commonly used in Chinese vernacular dwellings. During winter nights, when the ambient air temperature can be below – 7 °C, residents are able to sleep comfortably in their bedrooms – the thick exterior wall, air gap, timber panels lining the bedroom, canopy bed and one or two layers of thick quilts both underneath and above the occupants' bodies all contribute to this.

In winter, residents of the villages seek the most comfortable space to stay when they are not doing things that require them to be in a particular place. When the space they are in is not thermally comfortable they make their bodies thermally comfortable by various means instead of or in addition to heating the whole space.

Figure 7. 17 Canopy bed showing the whole view (Source:http://www.songhetang.cn/hotel-45.html)

7.6 Conclusion

The adaptive comfort model was used for evaluating the thermal comfort in Chinese vernacular dwellings because these dwellings are all free-running buildings that have been occupied for hundreds of years; residents were seen to use various measures to make themselves comfortable and these measures widen the range of comfort temperatures in their houses.

It was found that one particular part of the houses studied in each of the three villages was occupied more than others at any time of day, so consideration of the most occupied space is of value in assessing the thermal functioning of the dwellings. The residents of the three dwellings studied in Xidi village spend most of their daytime in the hall and skywell since they run souvenir selling businesses within their houses. Most residents of the houses studied in Zhifeng village and Yuyuan village were absent from the skywell dwellings for most of the daytime, except the old and children. In Zhifeng, the children and the elderly prefer to stay in the yard, hall and skywell during the daytime while in Yuyuan village people in these age ranges prefer to occupy the veranda and bedroom in the daytime.

While it would be expected from the results based on an adaptive comfort model which make use of psychrometric charts, a high proportion of village residents would be dissatisfied with the thermal environment in their most occupied spaces; these residents were found to be generally satisfied with the thermal comfort of their houses in questionnaires. It is likely that, the inhabitants of the villages are more tolerant of high humidities than the ≤ 90% RH boundary allows when natural ventilation was present. Through natural ventilation, evaporative cooling can still be exploited in humid conditions in skywells because it promotes movement of air to ensure exchange of air between the exterior and the interior. Such air movement is desirable to improve the thermal comfort for residents in hot and humid conditions.

Residents were seen to take various measures to maintain or restore their thermal comfort. In hot summer weather, besides wearing light clothes (0.5 clo), residents prefer to stay in shaded transitional spaces (such as that beneath the veranda); they also keep doors open, seek to maximize air flow, and cover the skywell with a piece of cloth. In cold winters, besides wearing heavy clothes (3 clo), residents use various traditional kinds of warming stove, seek exposure to the sun and sleep inside traditional canopy beds.

8 CONCLUSIONS

8.1 Introduction

Chinese vernacular dwellings have existed for hundreds of years. They are all low-energy buildings constructed without external services at the time of construction. However, since then they have been adapted to include artificial lighting. These dwellings were not created according to a design plan, but evolved gradually in response to the social, cultural, economic, defensive, religious and environmental conditions of their regions. Much research has been published which is concerned with the architectural history, culture, layout, form, structure, materials and decoration of Chinese folk dwellings. However, little work has been published that incorporates an assessment of the environmental performance of these buildings, and little of that is exacting or comprehensive.

The principal aim of this research was to investigate the environmental performance of Chinese vernacular skywell dwellings quantitatively and to establish a model of rigorous and comprehensive qualitative and quantitative research in this area. This was done by analysis of on-site measurements and computer simulation of the environmental performance of vernacular skywell dwellings in three villages in south-eastern China – Xidi, Yuyuan and Zhifeng. Environmental performance and building form are examined in relation to current knowledge of the social and economic life of the villages in the 17^{th}–20^{th} centuries, and to the environmental comfort and the activities of present-day residents of traditional houses.

The thesis is divided into eight chapters. The objectives of the study and seven research questions were presented in chapter 1. The methods used to carry out the research and to answer the research questions were also described in this account. A review of the literature on Chinese vernacular dwellings was provided in chapter 2. In chapter 3, the environmental context of the three villages was discussed in detail. Research questions 1 'What is the typical dwelling form in each village?' and 2 'What is the architectural relationship between the geographical location, climate and social background of a village, and individual dwellings?' were also answered. In chapter 4, some basic information about a total of eight houses in the three villages studied including building dimensions and photographs was presented, and research question 3 'Are any features common to the individual dwellings in each village? What are the differences between dwellings in different villages?' was answered. In chapters 5 and 6, the quantitative environmental performance of the dwellings including daylighting and thermal performance were described and analysed in detail using data collected on site. Research questions 4 'How comfortable are the residents of these vernacular dwellings in respect of temperature, illumination and humidity?' and 5 'How good is the environmental performance of skywell dwellings, as assessed by rigorous quantitative analysis of daylighting and thermal performance in summer and winter?' were also answered. Thermal comfort in skywell dwellings was evaluated in chapter 7, where research question 6 'How do residents achieve thermal comfort in summer and winter?' was answered. In the present chapter (chapter 8), the literature review, the methodology and the main contributions including the answers to the research questions are summarized. Limitations of the study and suggestions for future work are also presented.

8.2 Summary of the literature review

Chinese and western researchers have studied Chinese traditional dwellings for several decades. In the early stages of this research, individual dwellings were observed and photographed and then groups of houses in particular areas of China were surveyed and recorded. Since the 1980s the aesthetic, historical, cultural, and geographical aspects of folk dwellings have been studied as well. Villages have also been considered as aggregations of individual dwellings. The categorization of vernacular dwellings has been the subject of research since 1950s.

Existing published research on Chinese vernacular dwellings is largely concerned with the architectural culture, layout, form and structure of buildings, building materials and decoration, and the architectural setting and historical circumstances within which dwellings were constructed. However, less work has been done on environmental aspects of the Chinese traditional house. The few published studies, have provided only anecdotal descriptions and semi-quantitative analysis of the influence of building type, building materials, and method of construction upon environmental performance. It is difficult to evaluate the thermal, daylighting and ventilation performance of vernacular houses on the basis of published work. There is a need for quantitative investigation of the internal climatic environment of Chinese folk dwellings.

The forms of Chinese folk dwellings vary throughout China due to differences in geographical features and climate, local materials, defensive requirements, economic conditions and the influence of religious considerations. Folk dwellings can be divided into eight types according to the plan and external form – courtyard houses, Hakka rammed earth houses, stilt house, overhanging houses, flat-roof houses, cave dwellings, tent dwellings and watch towers. Among the different forms of Chinese dwellings, the courtyard house is the most common type of Chinese folk house and is distributed extensively in China. Courtyard-style houses vary in detail according to climate, geographical location, social and economic conditions, and local architectural custom. The most typical form of courtyard houses in the north of China is the one-storey 'four-in-one' courtyard house. The courtyard houses in the south are mainly two- or three-storey houses with high gables and a relatively small and compact courtyard termed the skywell.

The configurations of these skywell houses are derived from the four-in-one courtyard houses of Beijing. As this basic pattern spread through China, it was modified to adapt to different physical locations, climates and economic conditions giving rise to important regional variations. In the south-east, where the economy was more prosperous, available land was scarce and the density of population greater, single-storey houses like the courtyard dwellings of northern China were not able to accommodate enough people in a given area and therefore multi-storey houses were built.

The subject of the present study was the vernacular dwellings with skywells in south-eastern China. The environmental performance of these skywell dwellings was studied quantitatively and in depth.

8.3 Summary of the methodology

Three typical villages in south-eastern China were used to furnish examples of skywell dwellings – Xidi village (29.9°N 118°E), Zhifeng village (29.28°N 117.67°E) and Yuyuan village (28.77°N 119.66°E). A total of 8 houses were investigated in detail – the Yingfu dwelling, the Dunren dwelling and the Lufu dwelling in Xidi village; the Panmaotai dwelling and the Panxianxiong dwelling in Zhifeng village; and the Yufengfa dwelling, the Gaozuo dwelling and the Shuting dwelling in Yuyuan village. These dwellings were chosen because they are representative of the traditional dwellings in their villages. Permission to study them was obtained from the house owners.

The following methods were used to carry out this research.

Photographs and observations of buildings

Photographs of the interior and exterior of Chinese vernacular dwellings and general views of the villages were taken during the on-site measuring periods. These images were shown in Chapters 3 and 4 to complement the other forms of information obtained in the study of the three villages.

Resident Questionnaire

A questionnaire concerned with the daylighting and thermal performance of vernacular skywell dwellings was developed. This was for the collection of residents' views of the living conditions they experience in these vernacular dwellings, and for the assessment of comfort level in respect of illumination, temperature and humidity. Replies were obtained from 34 residents in Xidi village, 28 in Zhifeng and 30 in Yuyuan village. In the questionnaire, interviewees were required to give responses to various questions on a scale of one to five, with five being the most positive score, one the most negative, and three a neutral score. The mean score was calculated and used as an index of the mean satisfaction with or strength of feeling concerning various aspects of the internal environment of the dwellings in the three villages.

On-site collection of physical data

Winter data collection in the three villages took place from 29th December 2008 to 19th January 2009 and from 7th February 2009 to 20th February 2009; summer data collection took place from 1st August 2009 to 30th August 2009 and from 28th August 2010 to 10th September 2010. Site and building dimensions were obtained using a laser ruler and a tape measure; illuminance was measured using a 4-in-1 multi-function environment meter; air temperature and humidity data were collected using data loggers; air speed was recorded using thermal and vane anemometers; surface reflectance was measured using a photometer and building surface temperatures were recorded using an infrared thermometer.

Dimensions of the eight dwellings studied were obtained for computer simulation and to enable environmental data to be displayed in relation to building structure. The measured survey of these buildings provides a valuable record of this heritage. Illuminance was measured to enable quantitative analysis of daylighting performance within Chinese vernacular dwellings. Air temperature and humidity inside and outside the dwellings were recorded to obtain data for the quantitative analysis of thermal performance within these dwellings. Air speed data were used to examine the modes of ventilation within the skywell dwellings and their effectiveness. Surface temperature data were used to determine the rate of convective heat flow through the surfaces of the dwellings.

Computer simulation of solar illumination

Computer simulation using Ecotect was used for quantitative analysis of solar conditions within and around the dwellings. In the three kinds of simulation the parameters used were weather data from EnergyPlus, local topographic data, building dimensions, and default values for the properties of construction materials within Ecotect. In the simulation of direct solar radiation into the skywell void, data from the summer period (1^{st} Jun – 31^{st} Aug) were used.

1) Simulation of solar conditions within the three villages

It was not possible to observe the solar penetration within the whole village on site, so computer simulation had to be applied. Ecotect software was used to construct three-dimensional models of each village and its surrounding topography. The models were used to simulate solar exposure of and penetration into the village at the summer solstice, winter solstice and equinoxes from sunrise to sunset, with the assumption of a clear sky condition all day.

2) Assessment of direct solar radiation into the skywell void

The amount of solar radiation which penetrates into the skywells of the eight studied dwellings was calculated using weather station data from EnergyPlus and Ecotect software. Using site measurement data, three-dimensional models of the eight skywell dwellings were produced in Ecotect before carrying out the simulation. Use of computer simulation allowed longer periods to be considered than would have been possible with on-site measurement.

3) Determination of effect of mutual shading

In order to evaluate the effect of mutual shading in summer, the Yingfu dwelling in Xidi village was taken as an example. Indirect solar gain (the heat obtained through solar radiation incident on opaque surfaces) of the Yingfu dwelling was simulated using Ecotect software and climate data from Tunxi weather station. The house was modelled in Ecotect both as an isolated building and as a structure surrounded by the buildings immediately adjacent to it in Xidi village.

Thermal comfort criteria

In order to evaluate the summer thermal comfort provided by the skywell dwellings, temperature / humidity data obtained at 1-minute intervals throughout the daytime (06:00-18:00) of the one-week summer recording period for the most occupied spaces were displayed on the psychrometric charts. On each chart the boundaries of the thermal comfort zone with still air assumed are shown with a black line. These boundaries and the underlying temperature / humidity contours were plotted using Ecotect. In setting the boundaries of thermal comfort zones Ecotect applies the following conditions

- To set boundaries of temperature comfort zone, use the expression $T_n = 17.6 + 0.31T_{o,m}$, where T_n = neutrality temperature and $T_{o,m}$ = mean outdoor *temperature of the month.*
- At 50% RH the width of the comfort zone is $T_n \pm 2°C$
- Upper and lower AH limits are 12 gkg^{-1} and 4 gkg^{-1} (from ASHRAE Standard 55-81)
- RH in thermal comfort zone must not exceed 90% (i.e. 90% RH contour of chart must be a boundary of the thermal comfort zone if zone is in contact with that contour)

In constructing the psychrometric charts residents were assumed to be sedentary. Having defined thermal comfort zones on the psychrometric charts in which still air was assumed, thermal comfort zones were also defined in which air movements affording natural ventilation were assumed to occur. Air speed in skywells was taken to be 1 ms^{-1}, and those in halls and bedrooms were taken to be 0.2 ms^{-1}. On each of the psychrometric charts the boundaries of the thermal comfort zone with cross ventilation operating is shown with a red line.

8.4 Summary of the outcomes

A summary of outcomes relating to each of the research questions addressed in this thesis is given below.

Research questions 1, 'What is the typical dwelling form in each village?' and 2 'What is the architectural relationship between the geographical location, climate and social background of a village, and individual dwellings?' are answered in sections 8.4.1 and 8.4.2.

Research question 3, 'Are any features common to the individual dwellings in each village? What are the differences between dwellings in different villages?' is answered in section 8.4.3

Research questions 4, 'How comfortable are the residents of these vernacular dwellings in respect of temperature, illumination and humidity?' and 5 'How good is the environmental performance of skywell dwellings, as assessed by rigorous quantitative analysis of daylighting and thermal performance in summer and winter?' are answered in sections 8.4.4 and 8.4.5.

Research question 6, 'How do residents achieve thermal comfort in summer and winter?' is answered in section 8.4.6.

Research question 7, 'What environmental benefit is conferred by the skywell?' is answered in section 8.4.7

8.4.1 Environmental context of the Chinese vernacular dwellings

The vernacular dwellings in the three villages studied have been found to be well suited to providing the greatest possible comfort for occupants during the hot summers and cold winters that they experience.

The villages are all in hilly areas and have good access to water from hill streams. Although the height of the nearby hills limits the solar illumination of the villages, the hills allow Xidi village to receive at least 7.5 sunlight hours, Yuyuan village 7 sunlight hours and Zhifeng village 6 sunlight hours even at the winter solstice. Xidi is much closer to the nearby NW hills than the SE ones, thereby avoiding excessive overshadowing from the SE hills and ensuring that the village receives adequate sunlight in winter. Since the three villages are all surrounded by ranges of hills which act as natural wind barriers, the houses in the villages are shielded from the cold winter winds.

The dense arrangement of most of the houses in these villages provides effective mutual shading in summer (through the spot measurements, the mean air temperatue in the alley was 2.8°C less than the ambient air recorded on the roof). In the summer daytime, residents prefer to keep the external doors of traditional houses open – both the doors of the main entrance and the doors to annexes. This allows the interiors of the dwellings to be connected with the network of narrow streets and alleys within which the houses are located. Natural ventilation is thus made possible throughout the village. In winter, residents keep the doors closed to minimize heat losses due to the cold wind.

8.4.2 Void to floor relationships

Nolli plans of the three villages studied were drawn for the first time in the research described in this thesis. Three main types of skywell dwelling can be found in these villages: the three-in-one skywell house, the four-in-one skywell house and the H-shaped skywell house.

Through generation and inspection of the Nolli plans of the village it became apparent that in the three climatically similar villages, the mean size of the skywells differs considerably from village to village – large skywells were found in Yuyuan village (void area is 12.8% of floor area in average), medium skywells in Xidi village (void area is 5.7% of floor area in average) and very small skywells in Zhifeng village (void area is 1.4% of floor area in average). This can be explained by consideration of site measurements and information obtained from local residents in interviews.

House form is influenced not only by climate but also by the wealth of the occupants, their activities and the availability of building materials. Of the three villages in past, Yuyuan was the richest village of the three with about 80% of residents being in families engaged in business. Many people in Yuyuan made a living from trading and from owning restaurants and shops. They built large houses with many bedrooms to enable several generations to live together. These dwellings necessarily enclose a large central area, and the skywells of these houses can be regarded as courtyards.

In Xidi, about 60% of residents were members of household which obtained their income from business. Men engaged in business outside the village and came back home a few times a year. Skywells were mainly used by women, children and the old for domestic work and recreation. Since men of working age were rarely present, security of the house became a high priority in house design, so skywells are not as large as those in Yuyuan village.

Zhifeng's economy relied mainly on agriculture, with more than 60% residents being from farming families. The fields were generally about 1000m away from the farm workers' houses. Most of the farm labourers worked in the fields in the daytime. The skywells of houses in Zhifeng village were rarely occupied in the daytime and were mainly used for storage. Skywells were therefore quite small, and tools and stored items placed within them for protection from rain.

8.4.3 Local characteristics of dwellings in the three villages studied and inter-village differences

The eight dwellings fall into three categories of vernacular house design – three-in-one, four-in-one and H-shape. In each dwelling the core of the layout is a skywell, with accommodation on three or four sides (three-in-one or four-in-one house). The skywell and a hall opening into the skywell both lie on the central axis of the ground plan. The eight skywell houses consist of either two or three floors and all have the typical white projecting horse-head wall. The construction materials are very similar – an external brick wall painted with white lime, wooden (Chinese fir) roof frames and internal wall panels, and floors made of various materials including lime, sand, stone, tung oil and rice slurry, and brick tiles.

The local characteristics exemplified by the houses studied in the three villages and the differences in these characteristics can be summarized as follows.

House sharing arrangement

In Xidi village, one family owns the whole of a skywell house while in Zhifeng and Yuyuan villages; each skywell house is shared by several families. This is due to land and property reform in the early 1950s. Accommodation was reallocated according to local need, with two or more families being placed in some larger dwellings.

Water trough

Water troughs are common in the vernacular houses of Xidi and Zhifeng villages but are absent from houses in Yuyuan village. Rainwater is discharged from the skywell by a covered drain in Xidi and Zhifeng villages, but by a water channel in Yuyuan.

Horse-head wall

There are horse-head walls on four sides of the vernacular dwellings in Xidi and Zhifeng. In Yuyuan village there is a horse-head wall only on one side of the dwelling, the side incorporating the main entrance.

Position of staircase

The staircase is normally placed at the back of the hall in Xidi village, while in Zhifeng and Yuyuan villages, the staircase is at the side of the dwelling. In Xidi and Zhifeng villages, there is only one staircase in each house, while in Yuyuan village there are normally two staircases positioned symmetrically about the central axis of the skywell and the open hall.

Veranda

Verandas are a common feature of the vernacular dwellings of Yuyuan village but are absent from houses in Xidi and Zhifeng villages.

Column bases

Round bases of wooden columns can be found in Xidi and Yuyuan villages while cube bases are found in Zhifeng village

8.4.4 Quantitative analysis of daylighting performance of Chinese vernacular dwellings

The investigation of the natural illumination of Chinese vernacular dwellings is the first quantitative study of the distribution of natural light in these houses.

Two patterns of DF isolux contour in skywell dwellings were identified. Below the skywell of a four-in-one house, illumination from the skywell dissipates radially from the centre of the skywell. This results in concentric circular DF contours below the skywell. In three-in-one skywell houses (in which a skywell of small cross-sectional area is peripherally located) the concentric DF contours below the skywell are bisected by the wall adjoining the skywell (the skywell wall), giving rise to roughly semicircular contours concentric with the mid-point of the skywell.

Residents' satisfaction with the daylighting level in traditional houses of Yuyuan village was high with a mean score of 4.5. In Xidi village, the mean satisfaction was 3.6, while in Zhifeng residents returned the low mean score of 2.6.

Dwellings in Yuyuan village have a bright daylit appearance due to their broad skywells – mean values of $DF_{m,sky}$, $DF_{m,uti}$ and $DF_{m,hall}$ were 35.7%, 23.5% and 4.8% respectively. Dwellings in Xidi village have good daylighting in the skywell and utility area but poor daylighting condition in the hall – mean values of $DF_{m,sky}$, $DF_{m,uti}$ and $DF_{m,hall}$ were 9.4%, 5.6% and 1.3%. Dwellings in Zhifeng village have a very poor daylighting condition due to their small skywells – mean values of $DF_{m,sky}$, $DF_{m,uti}$ and $DF_{m,hall}$ was 1.7%, 1.3% and 0.8% respectively. Daylighting levels in the bedrooms of houses in Zhifeng and Xidi village, were very low because (a) the amount of light entering the skywell is restricted by the small size of the skywell, especially in Zhifeng village, and (b) the complex decorated window frames present in houses in these villages exclude a large proportion of light. The mean DF of bedrooms of traditional houses in Zhifeng and Xidi villages was less than 1%, which is very gloomy. In Yuyuan village, due to the presence of large skywells which allow abundant daylight to penetrate, and the use of large windows with simple frames, the daylighting condition within bedrooms was much better (the mean DF was more than 2%).

Measured illuminance values were found to correlate with the mean satisfaction with the natural illumination of their dwellings expressed by residents of traditional houses in the three villages. In Yuyuan village, where the large skywells give high levels of illumination, interviewees were very satisfied with the daylighting performance (satisfaction score 4.5). In Xidi village, skywell have a moderate cross-sectional area and respondents found the daylighting performance of their houses acceptable (mean satisfaction score 3.6), Zhifeng village skywells are small in cross-sectional area and residents reported low satisfaction with the poor daylighting they received (mean satisfaction score 2.6). Residents of Zhifeng village appear to be able to tolerate the very poor daylighting conditions in their houses since their mean satisfaction score was close to the neutral value 3. Residents of Xidi village gave a mildly positive score of 3.6 despite the poor daylighting in the halls and the gloomy bedrooms.

Historically, bedrooms in Chinese homes were regarded as sleeping areas which were only occupied during the night, so abundant illumination of these spaces was not considered a necessity. In the daytime, residents have always spent most of their time in the hall and the skywell, which together have been used as living spaces. (In Yuyuan village, as has been noted, present-day residents appear to be reluctant to make full use of the hall but use the bedroom instead, possibily because they do not feel a sense of ownership of the shared space, but this is a minor exception.)

The residents of all three villages tend to take actions to pursue satisfactory daylighting conditions. In Xidi village, residents tend to move themselves and any objects they are using in pursuance of a task in order to obtain better daylighting condition; in Zhifeng village, residents spend less time in the skywell or the hall due to the low illuminance level in their house; they generally prefer to be in the yard where illumination is sufficient. When external illumination is strong, residents tend to stay within the skywell but keep the house doors open. The extent of opening of the doors is adjusted by the residents. In Yuyuan village, residents prefer to stay under the veranda or in the bedrooms to avoid excessive daylight since the illuminance levels tend to be high even on overcast days.

8.4.5 Quantitative analysis of thermal performance of Chinese vernacular dwellings

This is the first comprehensive quantitative research on the thermal performance of Chinese vernacular skywell dwellings by on-site measurement.

In questionnaires, residents of the three villages reported that they could maintain thermal comfort in summer with the opening of doors and only infrequent recourse to the use of fans. The mean scores for satisfaction with thermal comfort in summer in Xidi, Zhifeng and Yuyuan village were 4.4, 4.0 and 3.4 respectively. The corresponding scores in winter in the houses were 2.0 in Xidi, 2.2 in Zhifeng, and 2.7 in Yuyuan, thus people generally felt cold but not severely so. Residents of Zhifeng and Xidi felt very humid in their houses in summer and returned unfavourable mean satisfaction scores of 2.3 and 2.6. In Yuyuan village, the mean satisfaction score was a marginally favourable 3.1.

In the summer measuring period, the fluctuation of DBTs inside the skywell reduced considerably in relation to the ambient air. The mean diurnal swings inside the skywell dwellings of Xidi village, Zhifeng village and Yuyuan village were 8.8°C, 12.5°C and 7.1°C less than those of corresponding ambient air respectively. The mean DBTs inside the skywells was found to be 2.6°C to 4.3°C lower than the mean external DBT in Xidi and Zhifeng villages but very close to the mean external DBT in Yuyuan village.

In summary, from the questionnaire and thermal recording data, it can be concluded that in summer the residents appreciate the space within the skywell since it was much cooler than the ambient air. In winter the residents found the skywell unacceptably cold, and found it necessary to take action to maintain the thermal comfort. It can thus be concluded that the design of Chinese vernacular skywell dwellings is mainly intended to counteract excessive summer heat than uncomfortable winter cold.

The vernacular dwellings studied have a stable and cool thermal environment within the skywells. This is achieved by the operation of a complex thermal system inside the skywell, which incorporates several heat inputs and outputs – radiative heat gain/loss, conductive heat gain/loss, convective heat gain/loss, evaporative heat loss, and heat gain from internal sources.

Chinese vernacular dwellings were found to have high heat capacity (the specific mass was calculated to be over 400 kg/m^2); their construction materials absorb heat during the daytime and release it during the night. In summer, heat from the sun accumulates in the construction materials, delaying the entry of heat into the dwelling; in winter, heat from the interior is retained in the fabric of the buildings, slowing the loss of heat to the exterior. This reduces the fluctuation of temperature within the skywell considerably.

Evaporative cooling did occur in the skywells of dwellings of Xidi and Zhifeng villages. The absolute humidity inside the skywells was generally higher than the ambient AH and the greatest difference (over 3g/kg) was found around 12:00. The water for evaporation is mainly from water trough and damp inner surface of skywell wall. Evaporative cooling occurred inside the skywell further reducing the temperature fluctuation inside the skywell and was the main reason that the mean DBTs inside the skywells being 2.6°C to 4.3°C lower than the mean external DBT in Xidi and Zhifeng villages. In Yuyuan village the mean internal DBT were very close to the mean external DBT since no evaporation appeared to occur.

The amount of solar radiation penetrating into a skywell dwelling is restricted when the skywell is small. Dwellings in Zhifeng and Xidi villages receive much less incident solar radiation through skywells than dwellings in Yuyuan village, due to the small size of the skywells in Zhifeng and Xidi. The mean daily solar irradiation incident upon the skywell in the summer period in Zhifeng village was less than 6KWh, in Xidi village less than 42KWh but in Yuyuan village over 110KWh. This is a reason that in site measurements the air in the skywells of the dwellings in Yuyuan village was hotter with larger diurnal swing than those in Zhifeng and Xidi even though the ambient air in Yuyuan was slightly cooler than that in Zhifeng and Xidi. The tall white horse-head wall and mutual shading of vernacular dwellings can reduce indirect solar gain considerably (eg mutual shading of Yingfu dwelling was found to reduce indirect solar gain by 35% in summer).

In Chinese vernacular dwellings residents prefer to keep the external doors open in summer; while in winter, residents keep the doors closed to minimise heat losses. It can be found that cross ventilation mostly occurred in the vernacular dwellings in the daytime with the doors open while the stack effect ventilation occurred mainly during the night with all the doors closed.

Air speeds at the inlets and outlets were much higher than those in the skywell; in the hall, air flow was very weak. Horizontal air speeds directly below the skywell, which are close to the main axes of air flow between the inlet and outlet to the buildings were higher than the speeds measured at points far from the axes. Vertical air speeds directly below the skywell were very low during the daytime while at night (eg. midnight) the mean vertical air speeds were found to be higher than 0.1 ms^{-1}.

Cross ventilation took place effectively at the daytime. It is a disadvantage at most of the daytime since more heat was brought into the skywell which could cause higher air temperature; however ventilation also promotes evaporation within the skywell, and hence evaporative cooling. Furthermore, air movement can produce a physiological cooling effect (see section 6.5.1). Stack effect ventilation took place at night. It is a great advantage to remove the heat inside the skywell through convection and evaporation, and recover the internal heat storage capacity for the following day. Radiant cooling is also likely to be important in recovering internal heat storage capacity. In skywell dwellings the skywell floor faces the sky directly, which could permit effective radiant cooling in cool summer nights.

Heat gain from internal sources such as electrical appliances and the bodies of the occupants had a small effect on the thermal condition of the skywell dwellings.

8.4.6 Thermal comfort

The occupants of traditional houses were found to be gererally satisfied with the thermal comfort of their houses in questionnaires. In predication of satisfaction based on an adaptive comfort model that incorporates existing empirically based findings on thermal acceptability, and which made use of psychrometric charts, it was concluded that residents should be generally unsatisfied with their level of thermal comfort. Residents appear to be more tolerant of high humidity with the presence of natural ventilation. Through natural ventilation, evaporative cooling can still be exploited in humid conditions in skywells because of movement of air to ensure exchange of air between the exterior and the interior. Such air movement is desirable to improve the thermal comfort for residents in hot and humid conditions.

Residents took measures to maintain or restore their thermal comfort. In hot summer conditions, besides wearing light clothes, residents were found to prefer to stay in shaded transitional spaces (such as under the veranda), to keep doors open, to promote the flow of air, and even to cover the skywell with a piece of cloth. In cold winter conditions, besides wearing heavy clothes, residents were found to use various kinds of stove, to allow themselves to be exposed to the sun, and to sleep inside traditional canopy beds.

8.4.7 Environmental benefits conferred by skywell

In a skywell dwelling, daylight for the skywell floor is supplied entirely by the skywell while the illumination of the bedrooms on the ground floor is entirely from windows facing the skywell. The daylighting level within a skywell dwelling is determined by the size and depth of the skywell, the presence or absence of skywell glazing and its transmittance, and the reflectance of surfaces within the skywell. The skywell provides sufficient daylight for residents to be able to carry out various visual tasks successfully.

The skywell dwellings were found to have high heat capacity; since the construction and composition of the skywells were representative of the whole house, the skywells themselves necessarily had high heat capacity, which reduces the fluctuation of temperature within the skywell. In hot summers, the amount of solar radiation penetrating into a skywell dwelling is restricted when the skywell is small. This leads to lower skywell temperature and smaller temperature fluctuations. In the daytime, the skywell appears to have little effect on ventilation; however, at night stack effect ventilation was found to occur with the mean vertical air speeds higher than 0.1 ms^{-1}. This form of ventilation was found to remove considerable amounts of heat from the skywell by convection and evaporation, thereby regenerating its heat storage capacity for the following day. In cold winters residents obtain warmth from direct sunlight that penetrates into the skywell.

8.5 Suggestions regarding the conservation of Chinese vernacular dwellings

Chinese vernacular dwellings are historically and architecturally important and every effort should be made to conserve them. However, in modern China, traditional dwellings continue to be destroyed and replaced with large numbers of buildings that have no national or regional design characteristics of any kind, yet which consume excessive amounts of energy.

Through the quantitative analysis of the daylighting and thermal performance of Chinese vernacular skywell dwellings and the evaluation of thermal comfort provided by these dwellings, it has been shown in this research that these vernacular dwellings are low-energy buildings with satisfactory daylighting and thermal conditions. Even if these dwellings were not of historical value there would be no need to replace them because their environmental performance is good and their occupants are satisfied with them. Some measures can be taken to make the present living environment in these houses even better. The following suggestions arise from observation of the sites during this research and from consideration of the results.

1 No new buildings, no reconstruction or extension or partial demolition of vernacular dwellings, nor any removal of original panels or other forms of remodelling of such dwellings should be allowed without permission from the local authority. Legal measures to protect such buildings should be enforced by an adequately staffed and funded body that is able to make frequent inspections of properties and give advice to property owners. Ancient buildings are already protected by legistation in China, but the law is unevenly enforced and instances of harmful adaptation and mutilation of historically important buildings are widespread, such as the removal for sale of decorative wooden panels from the Panxianxiong dwelling in Zhifeng village in the modern era.

2 As a matter of urgency, local govement should provide funding for repair and maintenance of traditional dwellings in the region visited in this study, since all the dwellings visited during this research were found to be damaged to some extent.

3 Better use should be made of space that is currently underused in the dwellings. In all of the houses investigated only GF rooms were fully used; higher floor levels were used for storage. This underuse of the upper levels can lead to their physical deterioration. These spaces should be converted into guest rooms for paying visitors, or other visitor facilities such as exhibition areas. In data collection visits it was found that all three villages are striving to attract tourists in order to improve the local economy; at present, many visitors have to stay in hotels nearby. Groups of visitors to the villages were heard to express disappointment at not being able to visit the upper floors of the dwellings.

Any adaptation of upper floor rooms should involve minimal alteration to the fabric of the buildings and should be in keeping with traditional styles of decoration.

4 Waste water should not always be discarded in the skywell, especially when the skywell is very small (such as the skywells in Zhifeng village). The splashing that occurs when water is thrown into a trough or onto the floor leads to the establishment of a very humid environment inside the skywell, which can encourage the growth of mould and mildew. Residents should be informed of the benefits of careful disposal of waste water and advised of the adverse consequences of poor disposal practices.

5 Glazed skywells such as the western skywell of the Lufu dwelling should be openable to facilitate natural ventilation.

8.6 Suggestions regarding the improvement of Chinese vernacular dwellings

As previously noted, the residents of the three villages reported satisfaction with the environmental conditions in their dwellings. This satisfaction may arise in part from their not having experienced better environmental conditions, leading to low expectations. Some of the traditional measures they employ to ensure thermal comfort in winter - such as sitting in a chair-type stove or wearing many layers of clothes - may be inconvenient, or restrictive, or uncomfortable, and may limit the quality of life of occupants of the houses by rendering certain activities difficult or impossible. Although the dwellings described in this thesis are of great architectural merit and of considerable historic importance, the conditions experienced by their residents are inferior to those enjoyed by the occupants of well-designed modern housing. In recent years China's economic success has been accompanied by rapid development in many parts of the country. In China's cities many people have experienced considerable improvement in the material quality of their life; this improvement ought to be shared by inhabitants of rural China. Within the villages studied, improved environmental conditions in the traditional houses would add to the comfort of the residents; this improvement would be worthwhile in itself, and it is also likely to raise the productivity of people engaged in business activities within the home, and hence to increase their prosperity. Enhancement of environmental conditions in traditional dwellings would also enable the occupants to engage in a wider range of recreational activities, and may even improve their physical health.

The current adaptations present inconvenience, which can be overcome - there are a number of passive measures that could be employed to improve the environmental conditions experienced by the inhabitants of skywell houses. Implementation of some of these measures may require guidance from people with specialist skills, and/or financial assistance. These could be provided by local government. Examples of measures that could be taken to achieve improvement in the internal environment of the houses are described below.

Installation of openable glazing over the skywells would help to accumulate and conserve heat in the cooler months in the closed configuration, while opening of the glazing would allow improved ventilation in summer. Glazing of the skywell would be practicable for all the three villages studied. Some parts of the houses were found to be highly uneven in their illumination, notably the bedrooms. Installation of additional windows in the bedrooms would improve illumination of these spaces and would provide opportunities for additional ventilation in summer. Therefore, the elimination of harsh contrasts between overlit and underlit areas of the dwellings can eradicate the problems of glare and of the need for adjustment to low light intensities as occupants move between different parts of the houses. Problems of glare in the vicinity of glazed skywells or windows could be mitigated unobtrusively by the use of blinds made of a transparent material that reflects or absorbs a proportion of incident sunlight.

However, any structural modification would require a significant alteration to the fabric of a historically significant building, and as such would be neither desirable nor permitted in Chinese law.

8.7 Relevance of the skywell design to present-day Chinese architectural design

The design of the traditional Chinese skywell house is a valuable inheritance that should be adapted and developed to contribute to contemporary design. Any design measures employed in the creation of these buildings that are intended to minimize energy requirements and ensure environmental comfort could be considered for use in practical building design today. Aspects of the design and construction of skywell dwellings that could be of environmental benefit in current design are described below.

Horse-head wall

Architects should be encouraged to include the typical tall white projecting horse-head wall in the design of new buildings, especially in the Huizhou area where the horse-head wall is a traditional feature. The light colour of the external wall surfaces increases the reflection of solar radiation, and the tall horse-head wall also shades the roof in hot summer and internally provides significant thermal capacitance which helps to stabilise internal temperatures. Examples of new buildings employing this design feature are shown in appendix I.

Skywell

Placing a glazed ceiling over a courtyard or skywell creates the modern form of the atrium, which has become a widely employed feature in building design. A high WI represents a tall and narrow atrium, which can give poor daylight levels in the lower part of the atrium and its adjacent spaces, while a low WI means the atrium is wide compared to its height, and thus can have good daylight conditions even in the lower levels (Littlefair and Aizlewood, 1998).

In the present study, it was identified that when WI of the skywell is less than 3, good daylighting condition (DF more than 5%) on the ground floor level can be achieved despite the low reflectances of the skywell surfaces, which ranged from 0.13 to 0.56 for the different materials present. In hot summers, the atrium should be openable to allow the operation of stack effect ventilation.

Evaporative cooling, night ventilation and hygroscopic materials

It is generally accepted that evaporative cooling can be exploited in hot and dry climatic conditions and that the combination of high thermal mass and night ventilation will not be effective in cooling buildings in hot and humid areas. In such areas, night-time temperatures are not much lower than daytime temperatures, and it is felt that massive buildings are not able to be cooled effectively during the night to recover their heat storage capacity for the following day.

This view is contradicted by the findings of the present study. The research was conducted in a hot and humid region, yet it was found *that evaporative cooling did* occur to an extent sufficient to influence the temperature in the skywells. Heat loss from the skywells by convection (as cool ambient air enters the skywell and warm air inside the skywell exits) was found to be limited since the temperature difference between the air inside and outside the skywell was small at night; it was concluded that much more heat was lost by evaporation, which was facilitated by stack effect ventilation. In addition in skywell dwellings the skywell floor faces the sky directly, which could permit effective radiant cooling in cool summer nights. This combination of effects appeared to be sufficient to regenerate the heat storage capacity of the skywell for the following day.

It can be further concluded that hygroscopic materials, high thermal mass and night ventilation can be combined for use in hot and humid areas in contemporary building design – these measures together promote evaporative cooling, and need to be accompanied by effective general ventilation for maximum effectiveness.

Use of hygroscopic materials creates a buffer for moisture in the same way as high specific mass construction creates a buffer for heat. The use of hygroscopic materials in building design deserves wide consideration in all climates where there are high ambient temperatures for some of the year. To exert their beneficial effects within buildings, hygroscopic materials must be exposed. This has the secondary benefits of saving the energy cost of surfacing materials, and ensuring that the air in the buildings is not contaminated by pollutants contained in materials of this kind.

Thermal comfort in locations of high humidity

In current building design, when a climate condition is very humid (RH>80%), architects would normally propose the use of air conditioning to dehumidify the air. However, in the present research it was found that residents appear to be more tolerant of high humidity than is implied, probably because of the effects of natural ventilation, and of acclimatization.

Architects should consider the maximization of natural ventilation before determining whether air conditioning is required, and – if it is – how powerful it needs to be. Through this approach it might be possible to achieve considerable savings in energy use.

It was found that predictions of thermal comfort based on psychrometric charts underestimated actual thermal comfort reported by residents. If this finding is replicated in other studies it may be necessary to modify existing systems for the prediction of thermal comfort, such as that which is incorporated in Ecotect.

8.8 Limitations and future work

This study has established a model for the assessment of the internal physical environment of small ancient dwellings. The main part of the work was a rigorous quantitative analysis of the capacity of Chinese vernacular skywell dwellings to provide acceptable daylighting and thermal conditions for their occupants, by natural means. This type of analysis could now be applied to any small house of traditional design.

Investigation of other types of vernacular dwelling within and beyond the borders of China would enable valuable and interesting comparisons to be made. For comprehensive assessment of the internal environment of ancient houses, air quality and acoustic characteristics should also be considered. This could usefully be undertaken for the dwellings investigated in this project, and in any new research into other types of house.

In principle, external illuminance values should be measured from a point where there are no obstacles, such as a rooftop. Access to rooftops was hard to obtain in the present study, so external illuminance was measured from large open spaces - such as village squares - instead. This may have reduced the accuracy of the results to a small degree. Ideally, internal and external illuminance values would have been obtained simultaneously, by using a pair of field workers. Since the present author was the sole field worker in this part of the study, the slight separation in time of the external and internal measurements is a source of error. This error is likely to have been minimal. Illuminance values obtained on overcast days are generally stable; and the author obtained sets of measurements by moving from the external measurement point to the room as quickly as possible. Error was reduced further by taking at least 3 complete sets of illuminance measurements in each room, with each set preceded by a measurement of external illuminance. The mean of the three values for each internal or external point of measurement was taken to represent the daytime illuminance at that point in overcast conditions.

Data on air temperature and relative humidity were only recorded for one week in summer and in winter due to limitations in access to the site locations, and in availability of data loggers and survey time. In the absence of further temperature and humidity data, the seasonal and year-to-year representation of the single-week data cannot be judged. Long-term measurement of air temperature and relative humidity in the houses is desirable.

Wind speeds were only measured for 10-minute periods concurrently with measurement of internal air flow. Wind speed and direction are highly variable, and can be strongly influenced in the short term by factors such as weather, human activities, and interactions with trees and nearby buildings that are hard to predict. For measurements to be representative they should be obtained continuously over periods of seven days or longer, using anemometers linked to laptop computers. Similarly, all the dwellings studied had been damaged or modified since their original construction, and most of the space contained numerous items of furniture and / or stored goods. This created complex airflow patterns that would need continuous measurement over long periods in order to obtain a truly representative and reliable picture of airflow within the houses. Simultaneous measurement of flow in many points within each house, and concurrent measurement of exterior wind speed, is desirable to ensure comparability and the securing of reliable data – in the present study, lack of equipments (only two anemometers avaliable), and the non-automated nature of those equipments meant that air flow could only be measured at a single point at a given time, with simultaneous measurement of air flow in the main entrance to provide reference data. This approach had the additional drawback of requiring airflow speeds to be expressed in relation to airflow speeds in the entrance, rather than as absolute values. Simultaneous measurement of airflow throughout the house would overcome this.

Many of the constituent materials of the skywells are hygroscopic. In this study strong indirect evidence was obtained for the operation of a quantitatively significant evaporation of water within the skywells of the studied dwellings. This should be confirmed by direct measurement *in situ*, and by laboratory experiments.

This research was mainly based on the site testing. In future investigations, advanced computer simulation for example, using the TAS software produced by EDSL, UK to examine the thermal performance of dwellings, and using open source Radiance software (produced by Larson and colleagues within the Lawrence Berkeley National Laboratory, USA) to study illumination within the dwellings more thoroughly; on-site data could then be compared with simulation results.

In daylighting simulation, vernacular dwellings can be modeled in Ecotect using measured values of building dimensions and properties of the building materials including the surface reflectance of these materials. In the subsequent lighting simulation, Ecotect (which uses a split flux method) is much less accurate than Radiance (which uses Monte Carlo method). Therefore, the model can be exported to Radiance to carry out the simulation. The effect of surface reflectance on the daylighting performance of the vernacular dwellings is difficult to examine through on-site measurements; however this can be investigated readily by changing the surface reflectance values of materials in a Radiance simulation and examining the effect of the changes. A basic structural model of the building can also be used for thermal simulation in TAS. TAS and other thermal simulation packages enable the thermal performance of vernacular dwellings to be analyzed over a long period and for different seasons to be considered.

The dwellings could be adapted to improve daylighting and winter warmth by analogous approaches. In the case of daylighting, illuminance and reflectance measurements could be obtained throughout a house of interest, and the data could be used to model the illumination of the house using Radiance software. This would enable areas of deficient illumination to be identified, and possible corrective measures evaluated (measures such as the introduction of tinted blinds or additional windows). Following refinement of these modifications in the simulation, they could be applied to the houses. Illuminance measurements could be taken on site again and evaluated, and the satisfaction of the residents measured by questionnaire and / or interview before and after making the modifications.

For improvement of thermal conditions, temperatures could first be measured throughout a house at different times and in different seasons, and the thermal characteristics of that dwelling could be modelled using TAS software. Through the simulation, areas requiring additional insulation could be identified; in particular, there are areas in the houses studied where it would be easy to add insulation in the gap between wooden panelling and stonework. The effect of glazing the skywells could also be modelled, in both closed and open configurations, as could the effect of adding a movable tinted blind layer beneath the skywell to moderate illumination in summer, or the addition of a second untinted blind layer to improve thermal insulation in winter. Temperature measurements could be repeated after making these changes, and (as for the daylighting) the satisfaction of the residents measured by questionnaire and / or interview before and after thermal improvement.

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APPENDIX A

Questionnaire – satisfaction with daylight, ventilation and thermal comfort in Chinese vernacular skywell dwellings

Questionnaire – satisfaction of daylight, ventilation and thermal comfort in Chinese vernacular skywell dwellings

Village ____________ Date ____________ Ref ____________

---

1. How old is your house?

<100 years ☐ 100 – 200 years ☐ > 200 years ☐ don't know☐

2. How many people live in your house?

[ ] people live here.

3. How many rooms are there in your house?

There are [ ] rooms.

4. How satisfied were you with the natural light in your house?

1	2	3	4	5
very dissatisfied	not satisfied	neutral	generally satisfied	very satisfied

5. If you are not satisfied with the daylighting condition, what do you do to improve?

[ ]

6. How important do you think the ventilation is in your house?

1	2	3	4	5
not important at all	unimportant	neutral	important	very important

7. How satisfied were you with the ventilation in your house?

1	2	3	4	5
very dissatisfied	not satisfied	neutral	generally satisfied	very satisfied

8. If you are not satisfied with the ventilation, what do you do to improve?

[ ]

9. How satisfied were you with the comfort in your house in winter?

1	2	3	4	5
very dissatisfied	not satisfied	neutral	generally satisfied	very satisfied

10. When the house is cold, what do you do to make it warmer?

11. How satisfied were you with the comfort in your house in summer?

1	2	3	4	5
very dissatisfied	not satisfied	neutral	generally satisfied	very satisfied

12. When the house is hot, what do you do to make it cooler?

13. How satisfied were you with the humidity condition in your house?

1	2	3	4	5
very dissatisfied	not satisfied	neutral	generally satisfied	very satisfied

14. When the house is humid, what do you do to make it drier?

15. How important do you think the skywell is for increasing the level of natural light in the house?

1	2	3	4	5
not important at all	unimportant	neutral	important	very important

16. How important do you think the skywell is for increasing the level of ventilation in the house?

1	2	3	4	5
not important at all	unimportant	neutral	important	very important

You have finished completing the questionnaire. Thank you very much for your help.

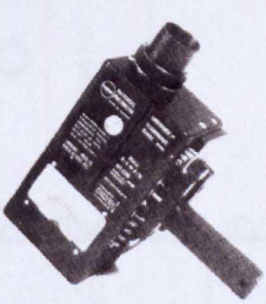
If you have any queries please contact: **Zhongcheng Duan**
email: laxzd3@nottingham.ac.uk **tel: 0044 7792671637**

APPENDIX B

Equipment used for on-site measurement

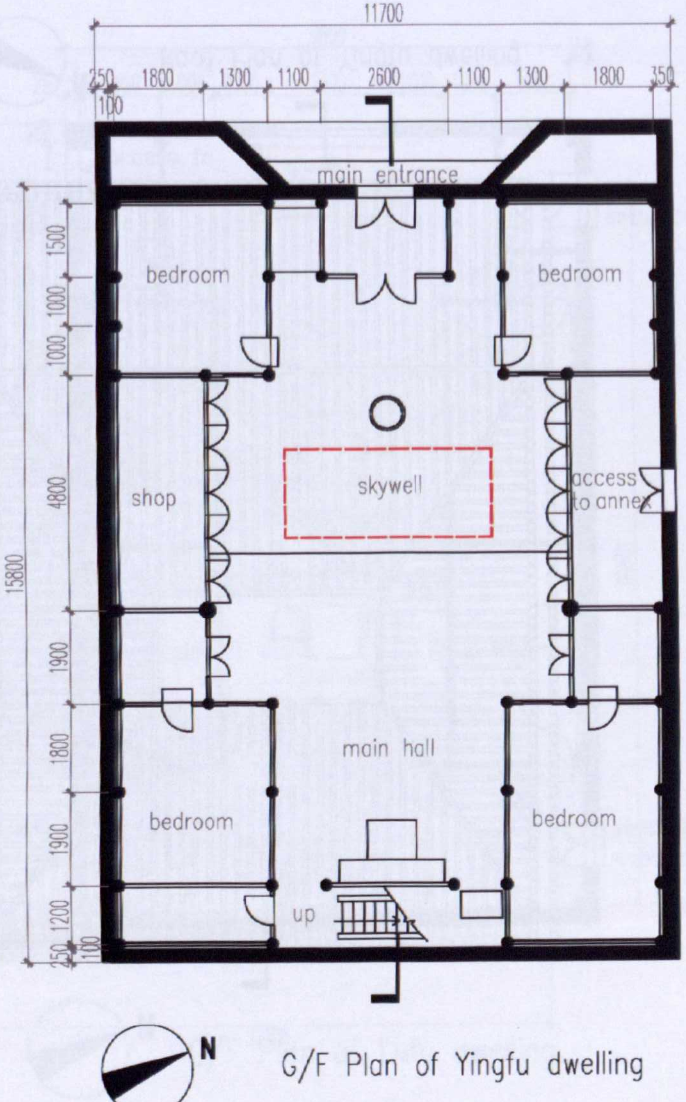
Table B. 1 Equipment used for the on-site measurement

number of equipment	name of equipment	image of equipment	description of the use of equipment
1	Laser Distance Meter (SW-50)		measurement of building and site dimensions
1	tape measure		measurement of doors and windows' dimensions
1	1m reference stick		calculation of the building dimensions according to the ratio between the stick and the wall in the photo
1	DT-8820 Environment Meter		spot measurement of illuminance, air temperature and humidity
16	Tinytag Plus2		recording of air temperature and humidity inside and outside the dwellings

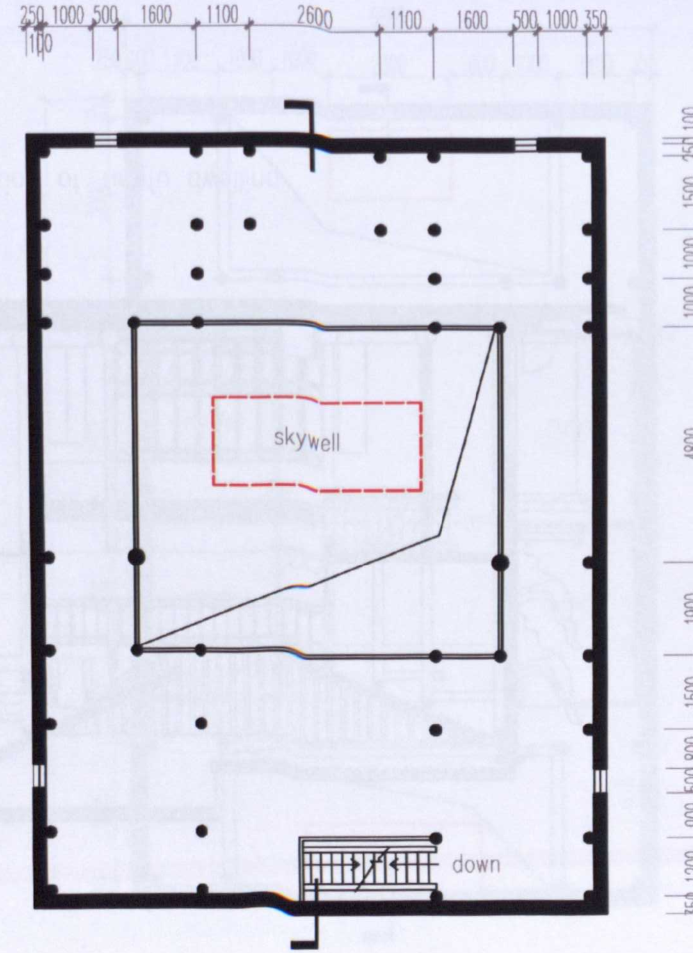
number of equipment	name of equipment	image of equipment	description of the use of equipment
2	Tinytag Hand-Held		recording of air temperature and humidity inside the dwellings
1	AIRFLOW TA2 anemometer/ thermometer		spot measurement of indoor air speed
1	AIRFLOW DVA 30VT		spot measurement of outdoor and main entrance air speed
1	DT-880B infrared thermometer		spot measurement of surface temperature
1	The Hagnar Photometer		spot measurement of surface reflectance

APPENDIX C

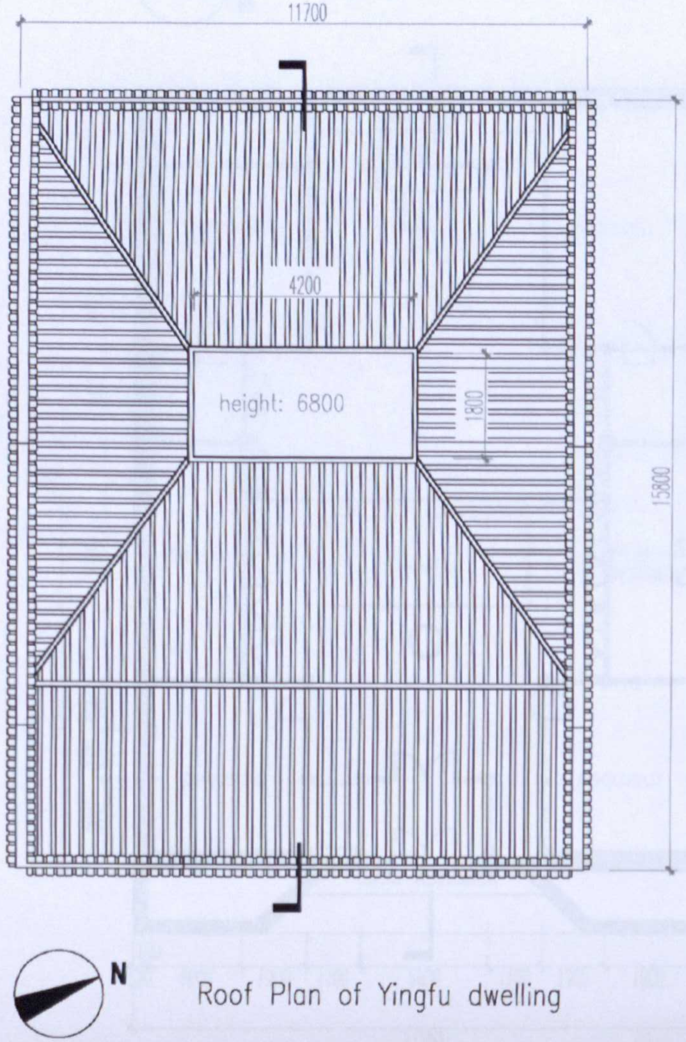
Drawings of the eight Chinese vernacular dwellings



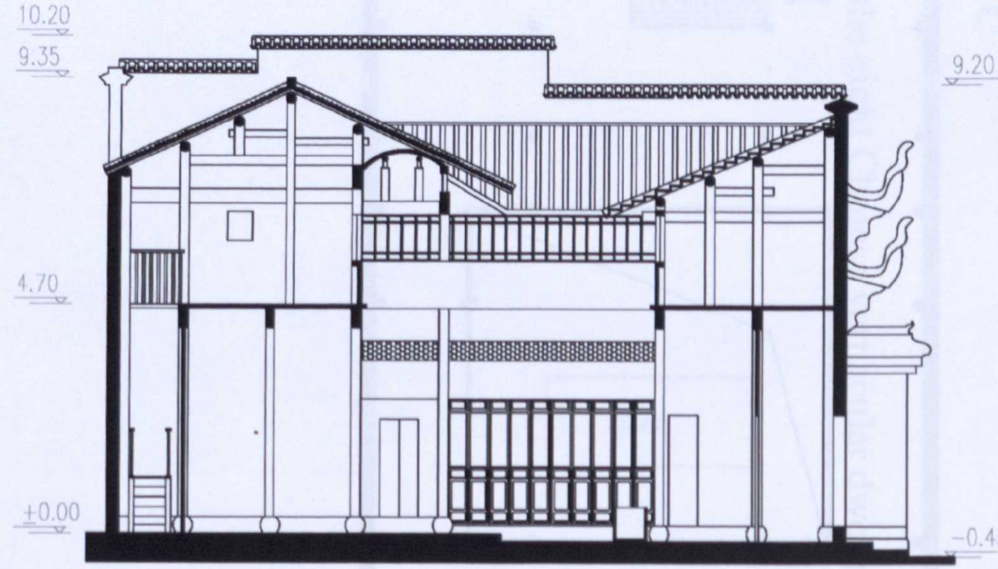
G/F Plan of Yingfu dwelling



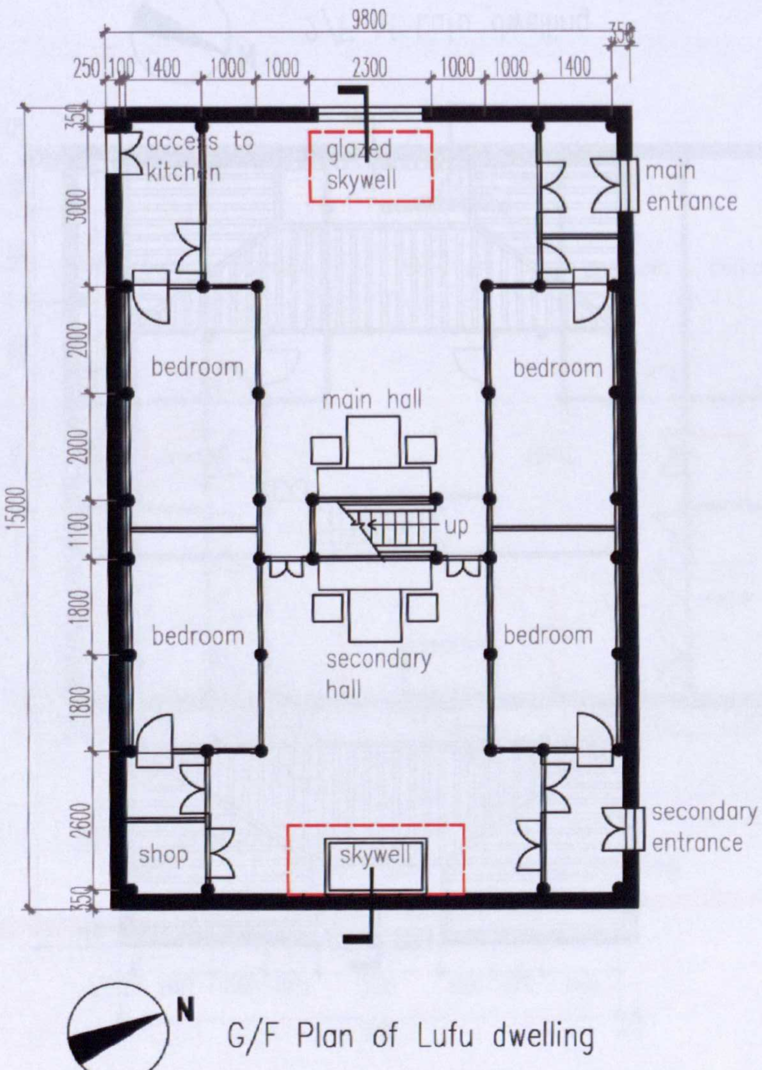
1/F Plan of Yingfu dwelling



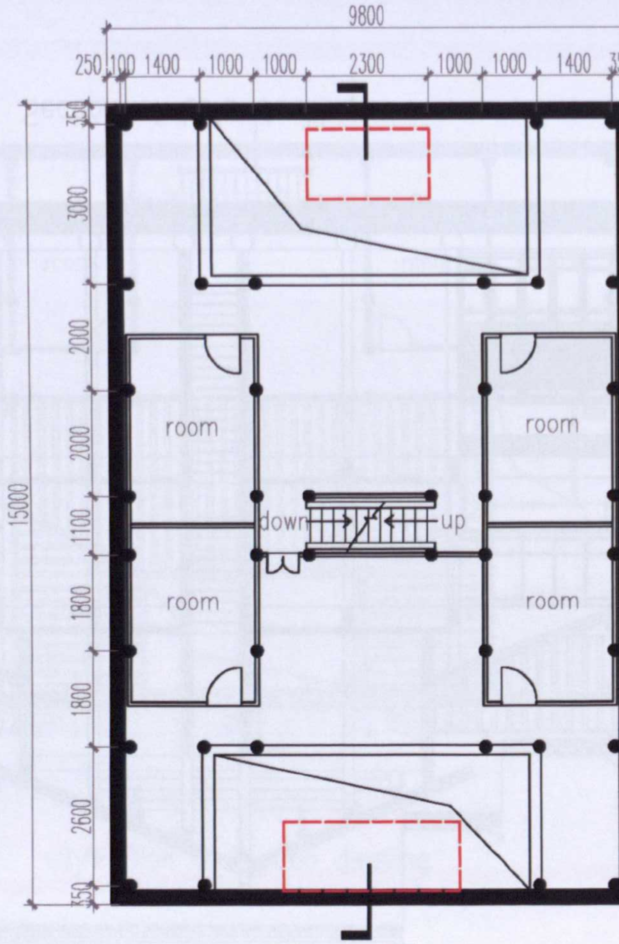
Roof Plan of Yingfu dwelling



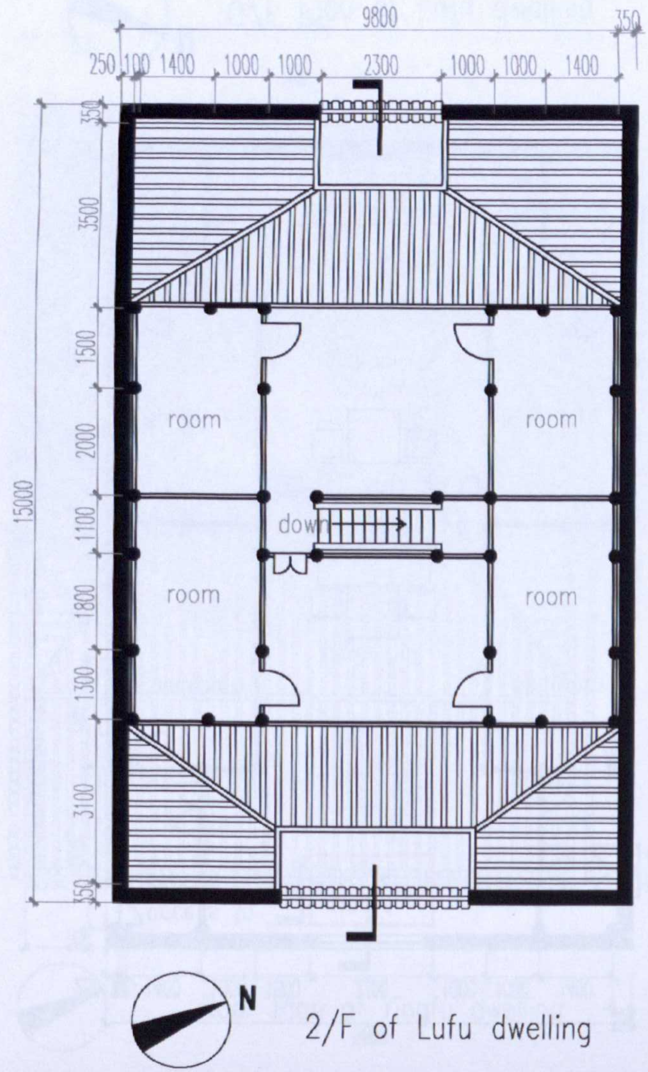
Section of Yingfu dwelling



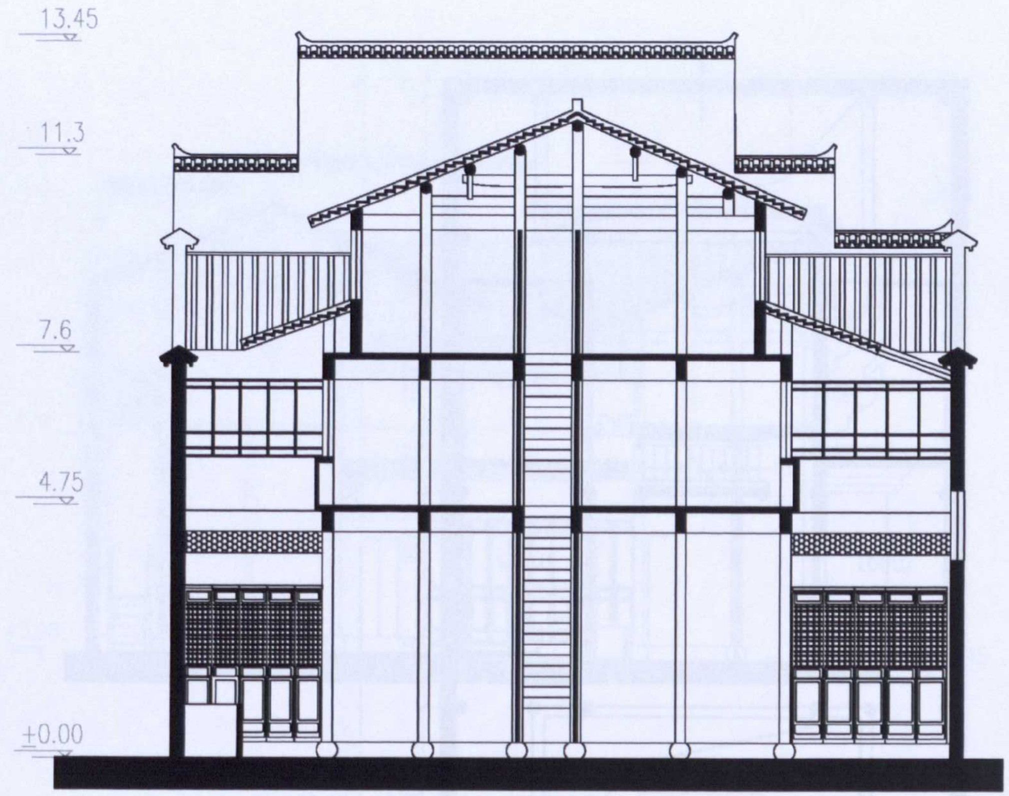
G/F Plan of Lufu dwelling



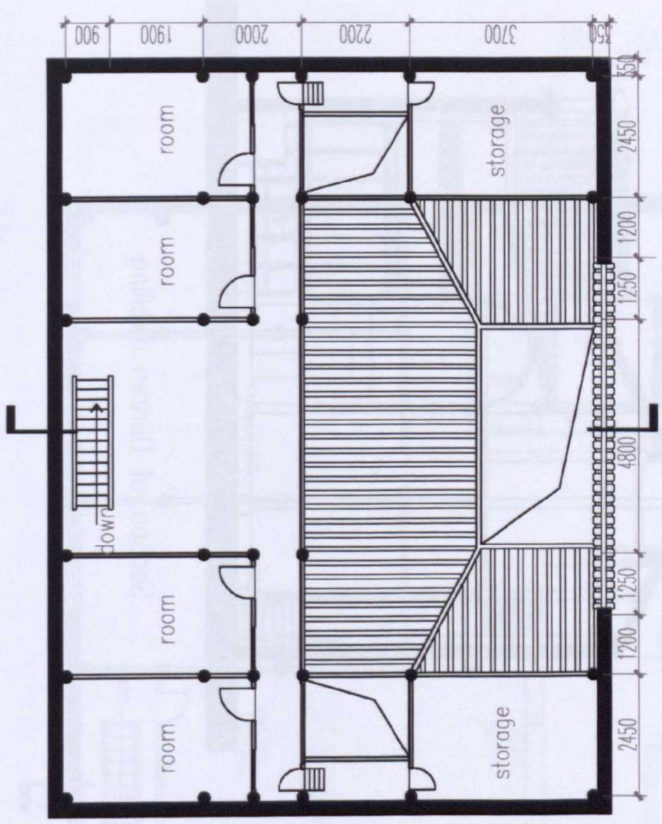
1/F Plan of Lufu dwelling



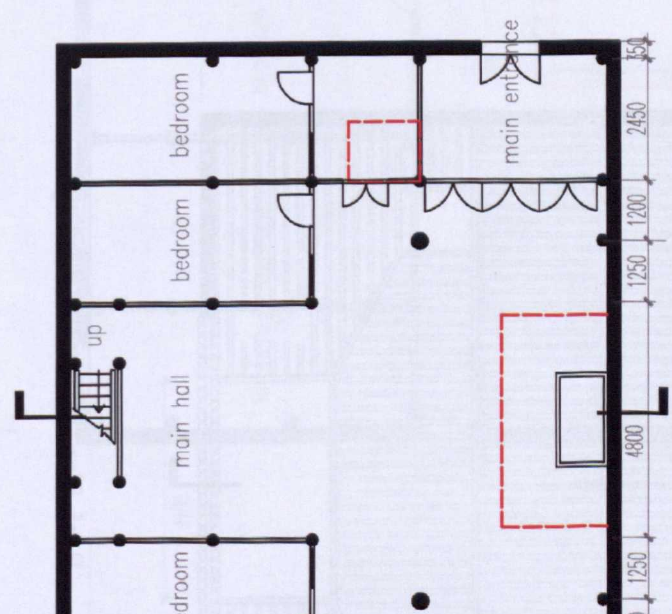
2/F of Lufu dwelling

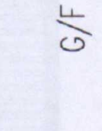


Section of Lufu dwelling

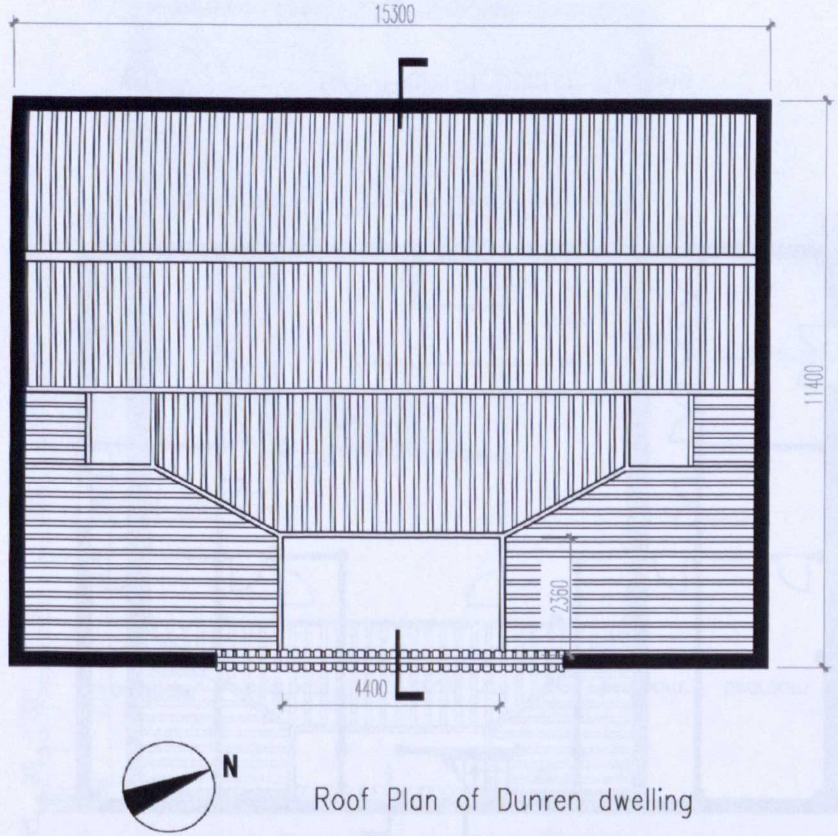


1/F Plan of Dunren dwelling

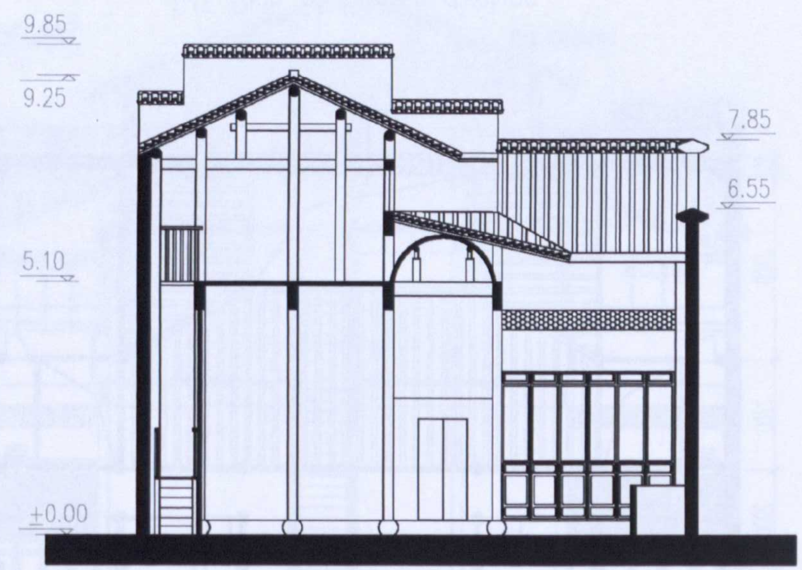




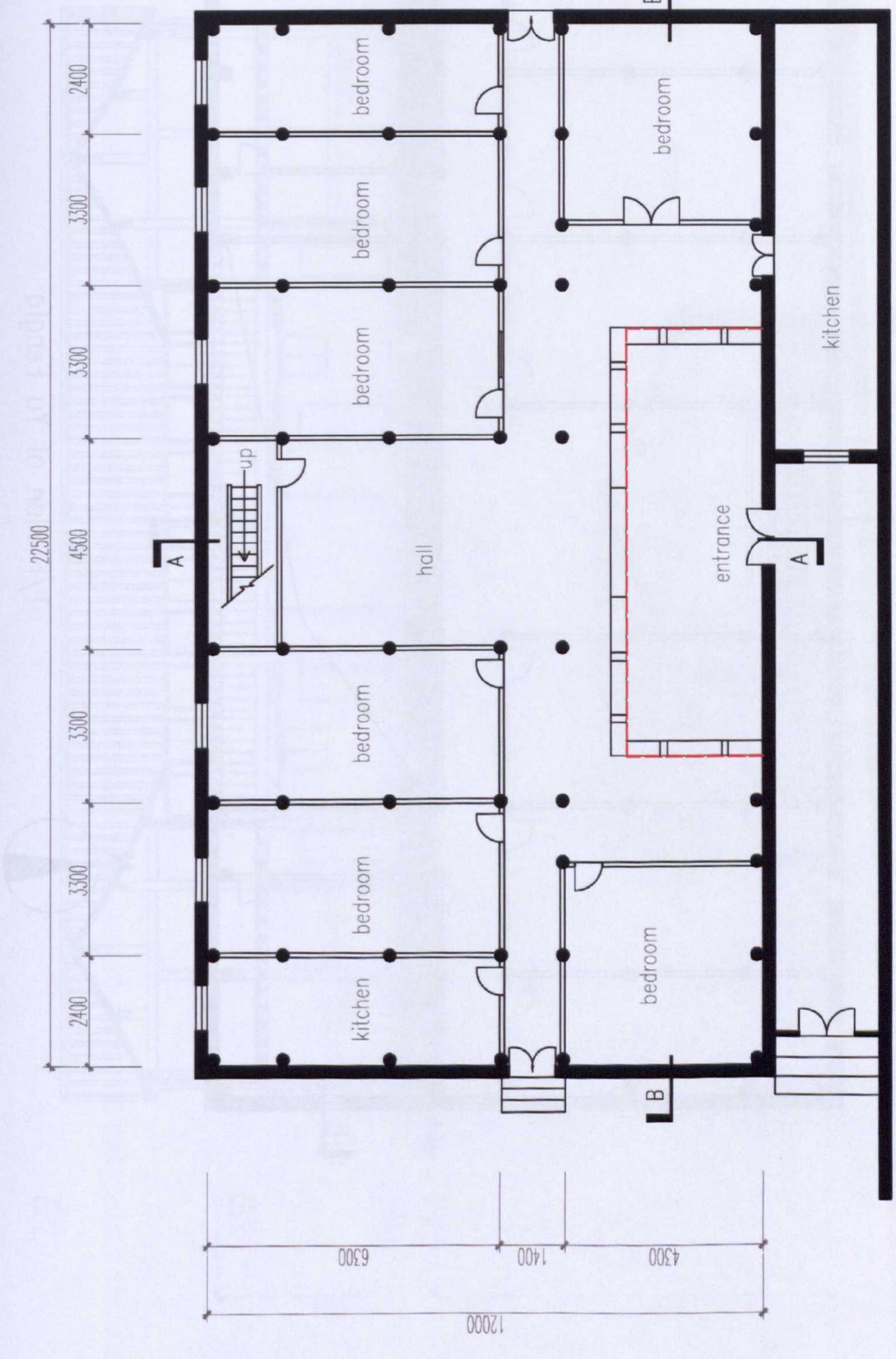
G/F Plan of Dunren dwelling



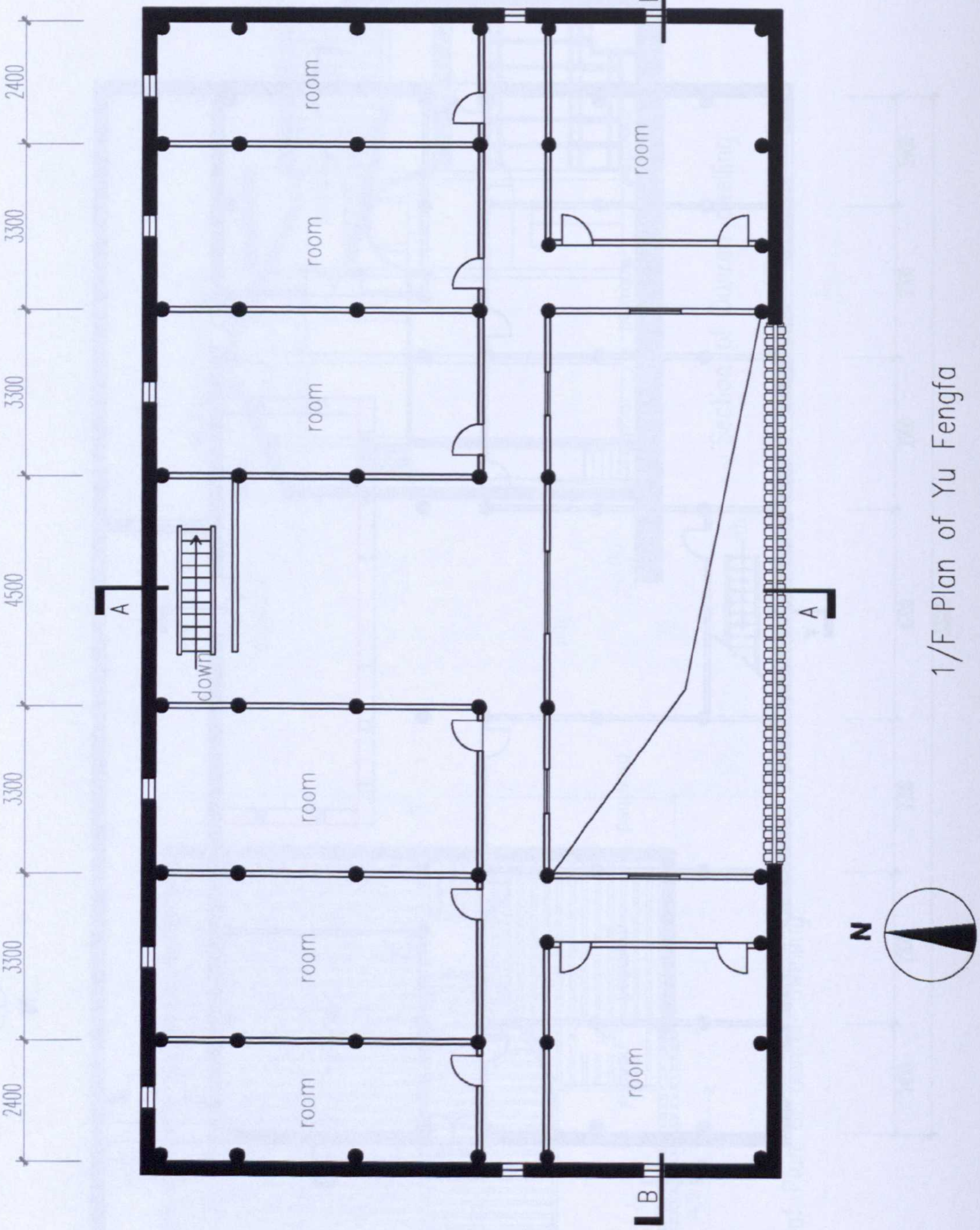
Roof Plan of Dunren dwelling



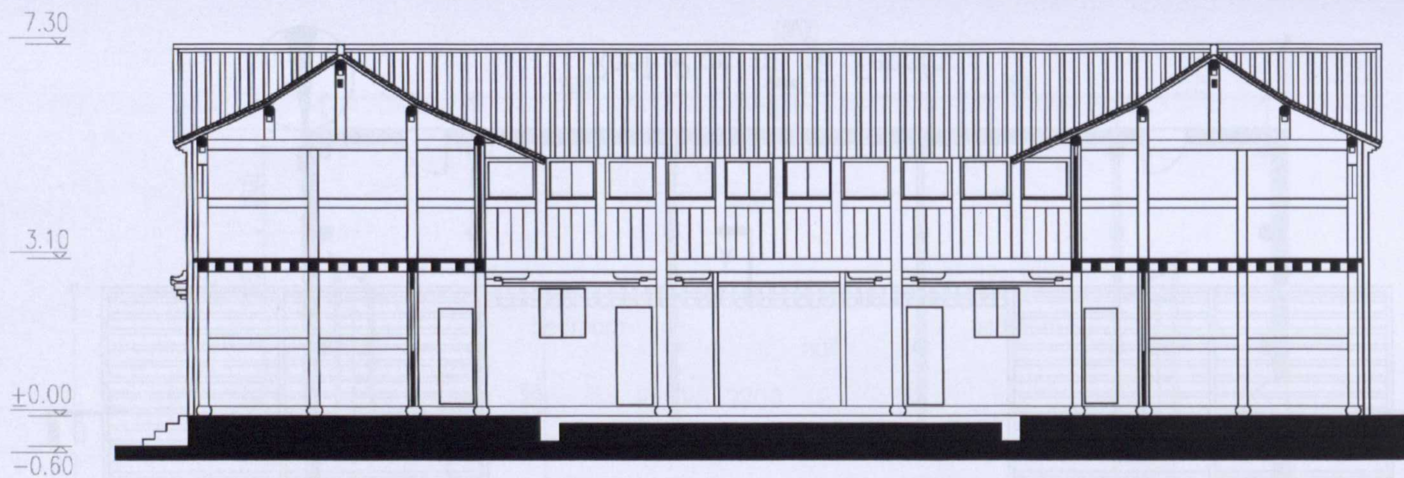
Section of Dunren dwelling



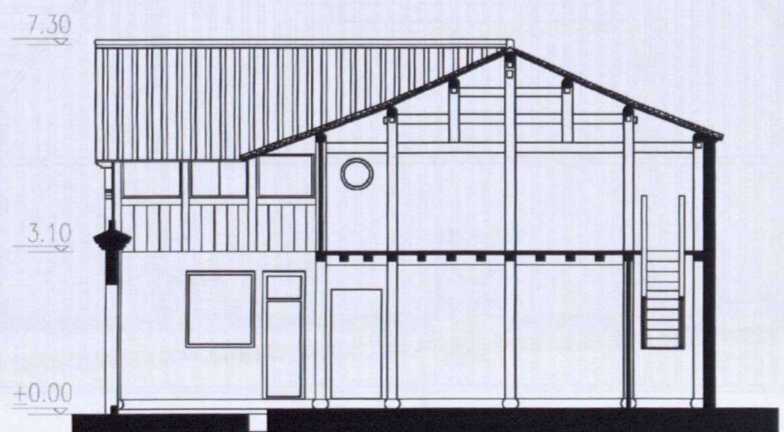
G/F Plan of Yu Fengfa



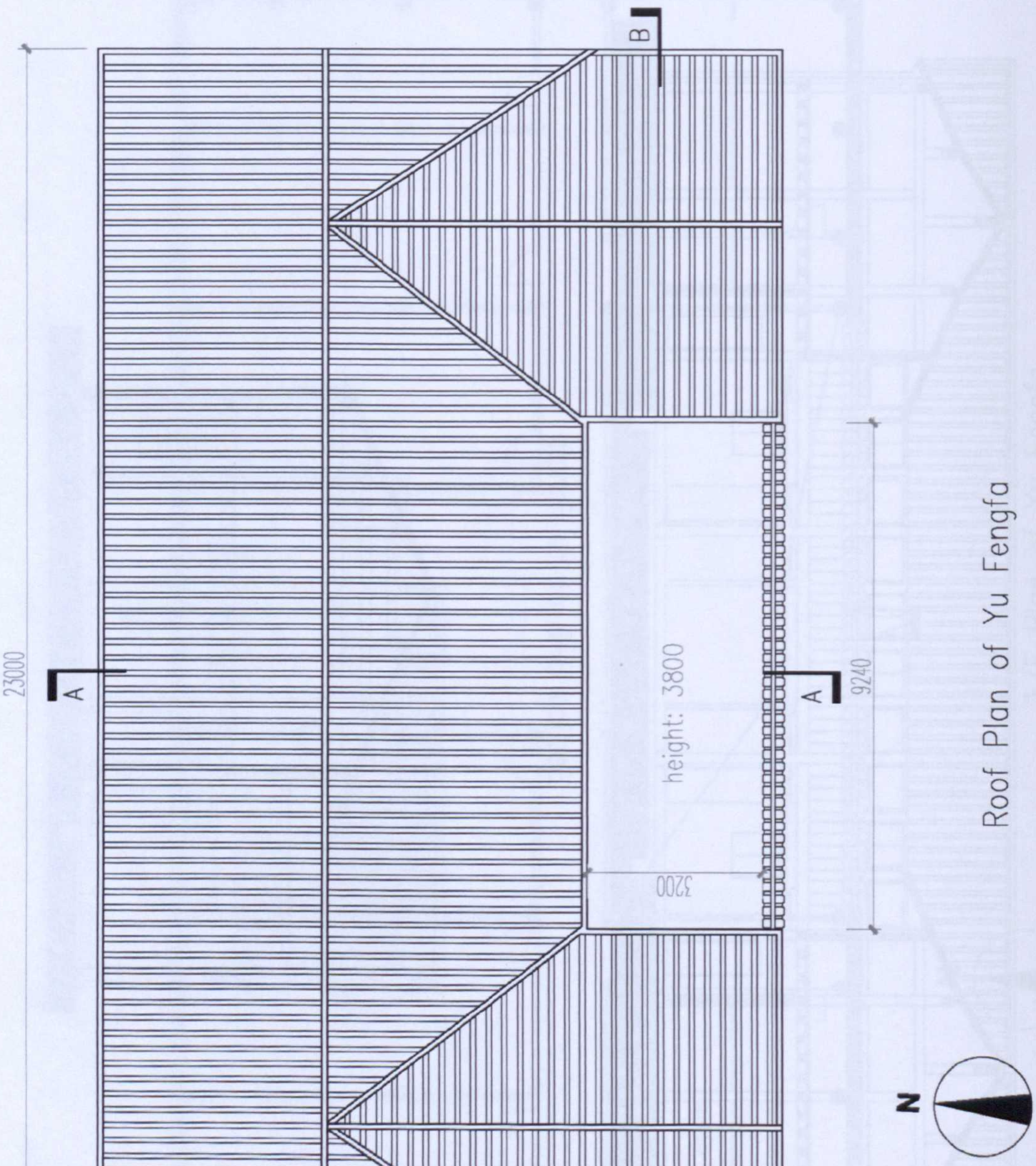
1/F Plan of Yu Fengfa



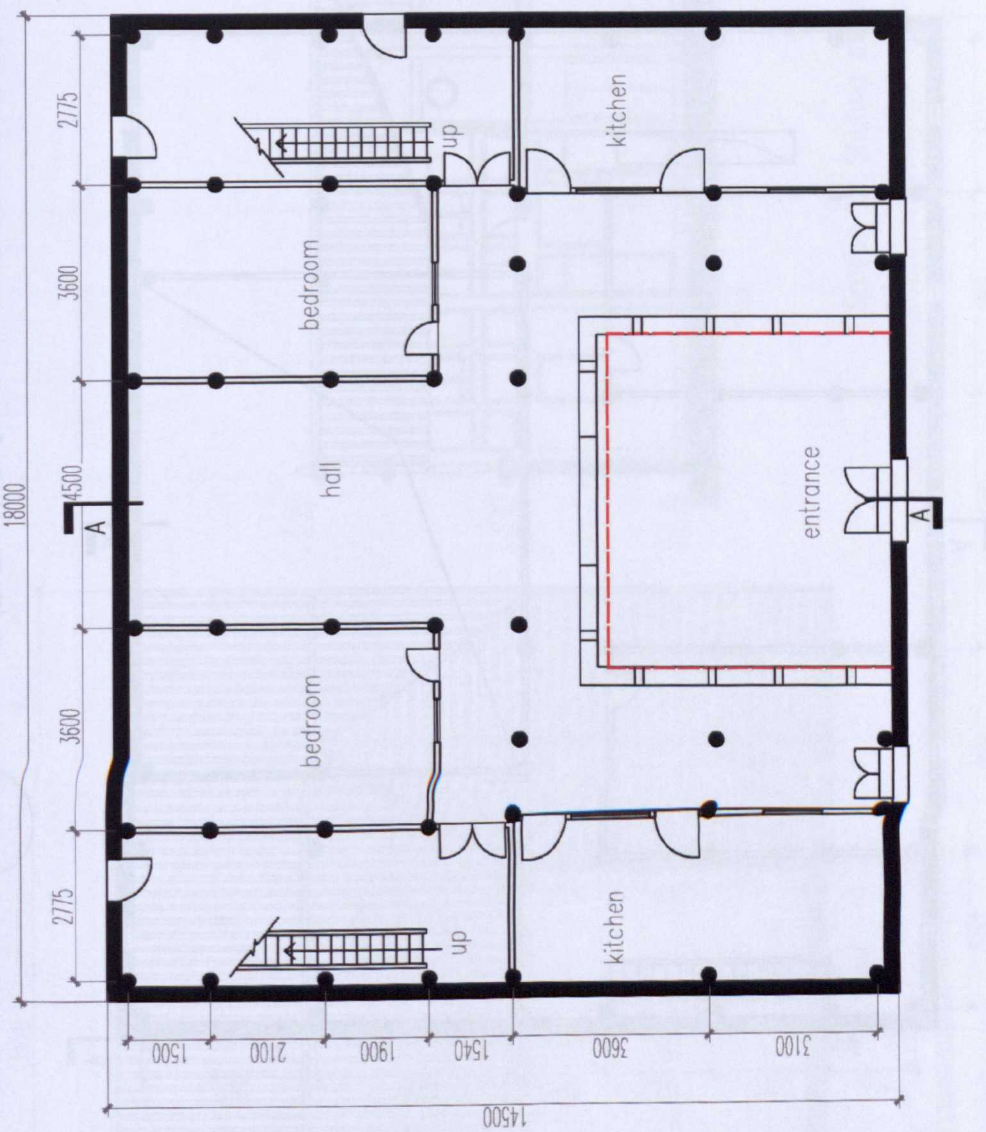
Section B–B of Yu Fengfa



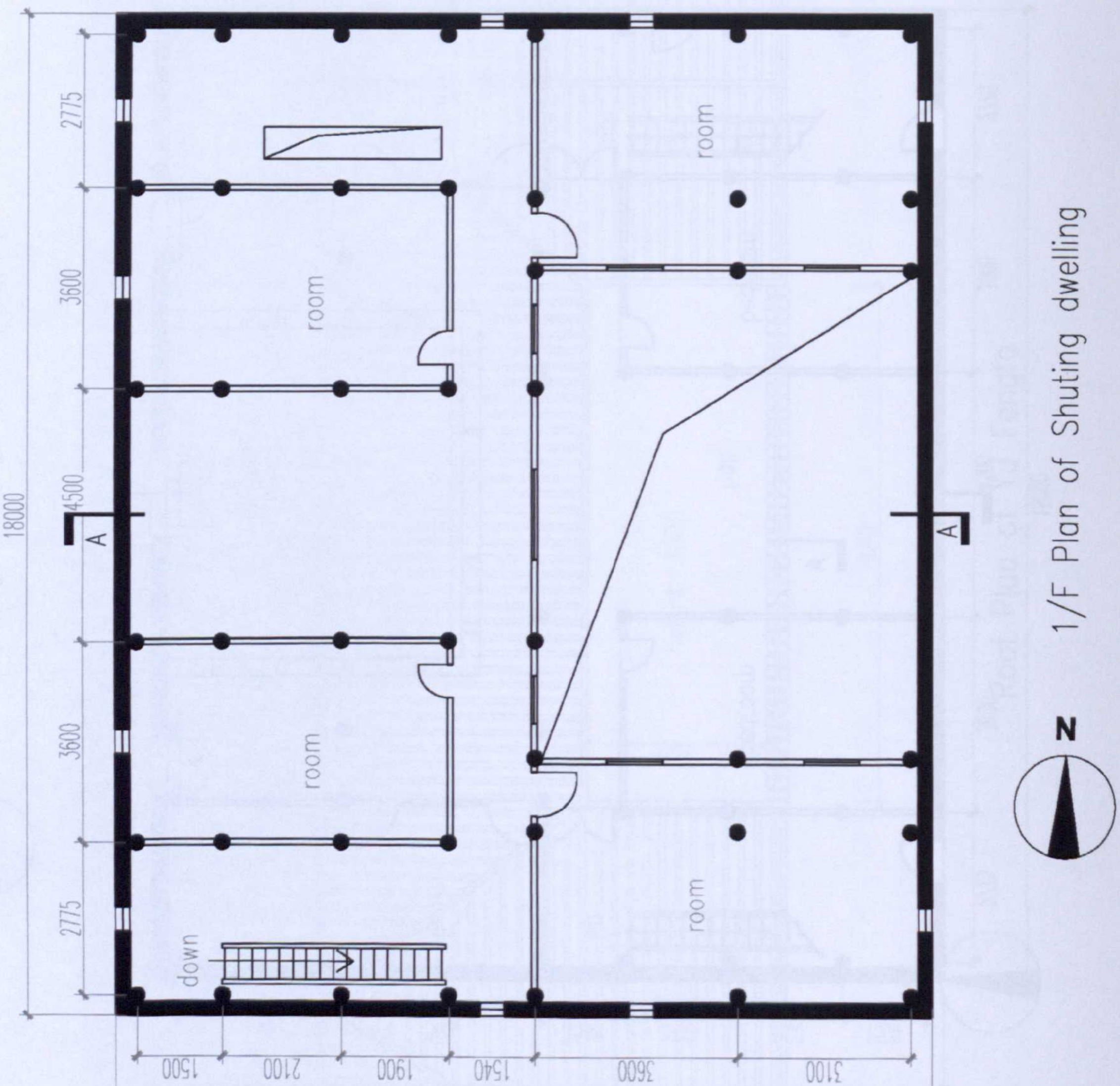
Section A–A of Yu Fengfa



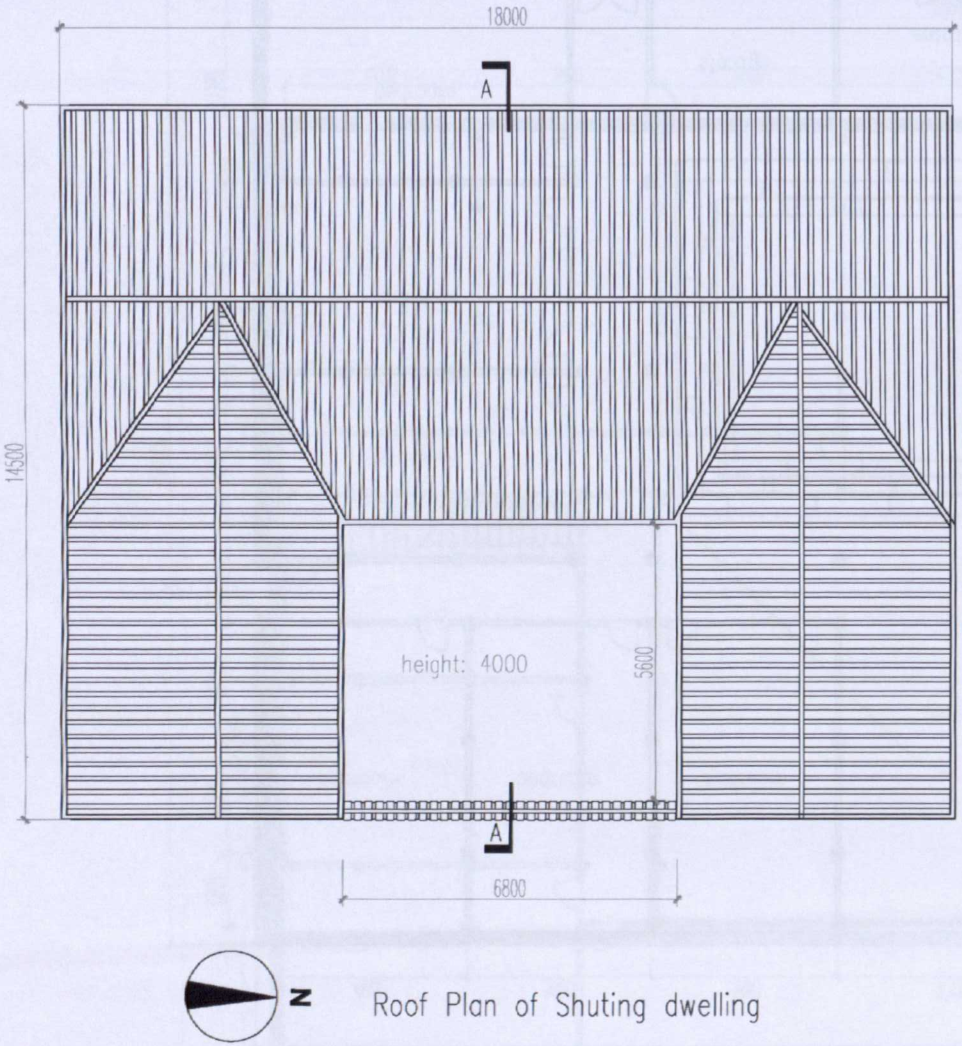
Roof Plan of Yu Fengfa



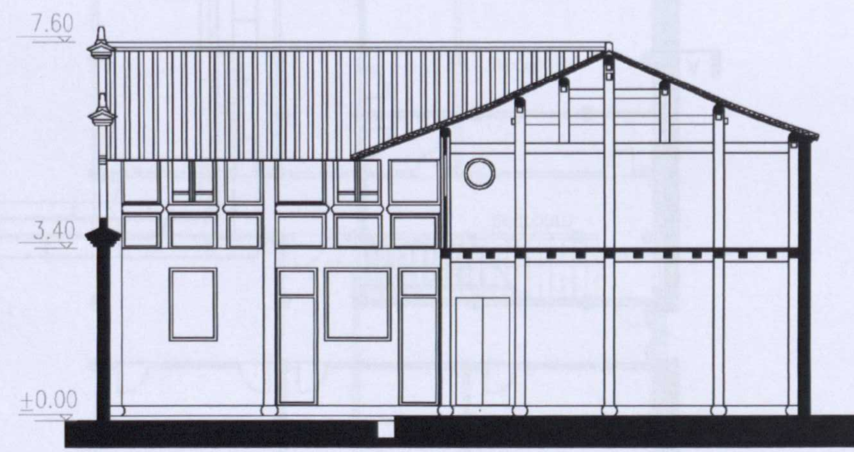
G/F Plan of Shuting dwelling



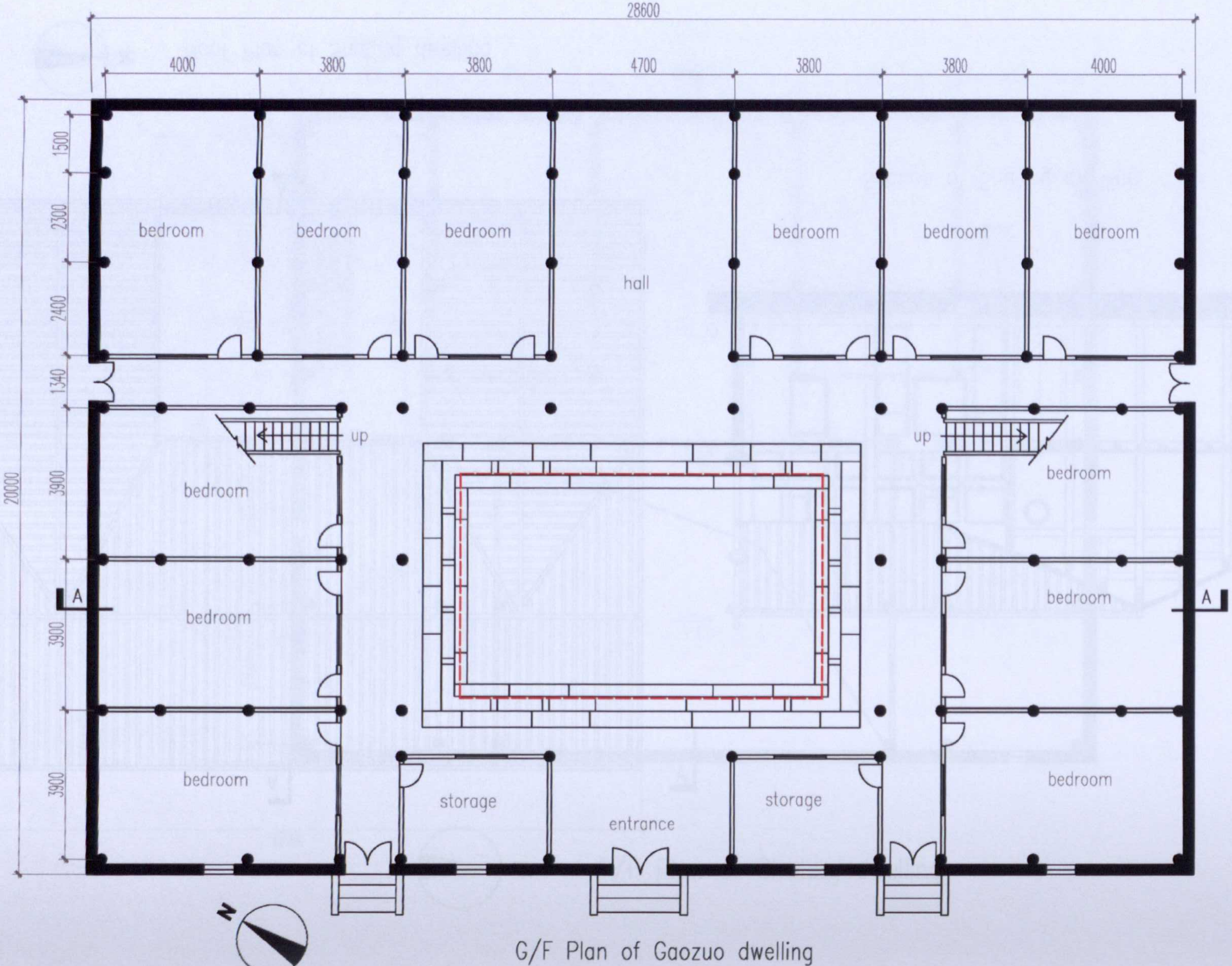
1/F Plan of Shuting dwelling



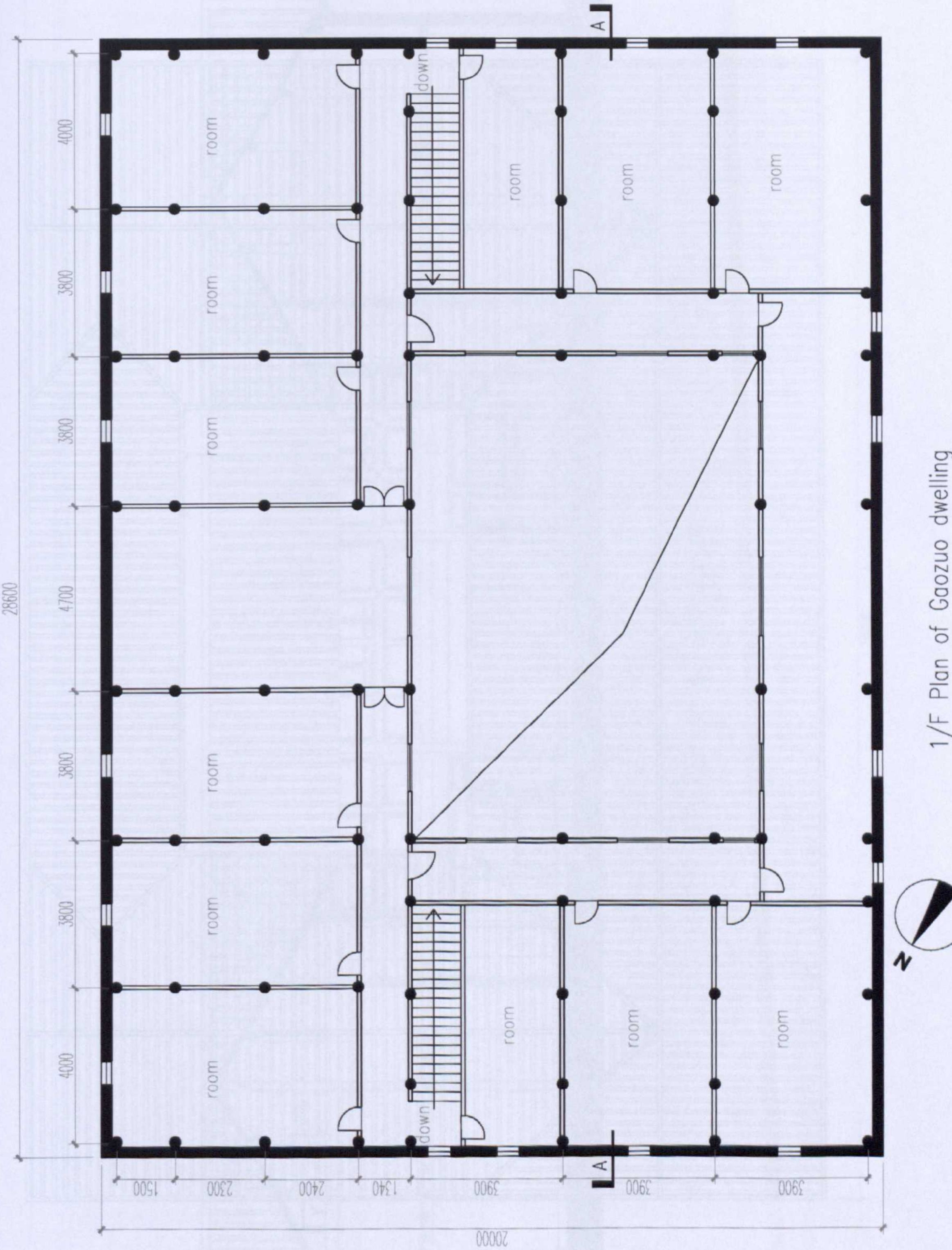
Roof Plan of Shuting dwelling



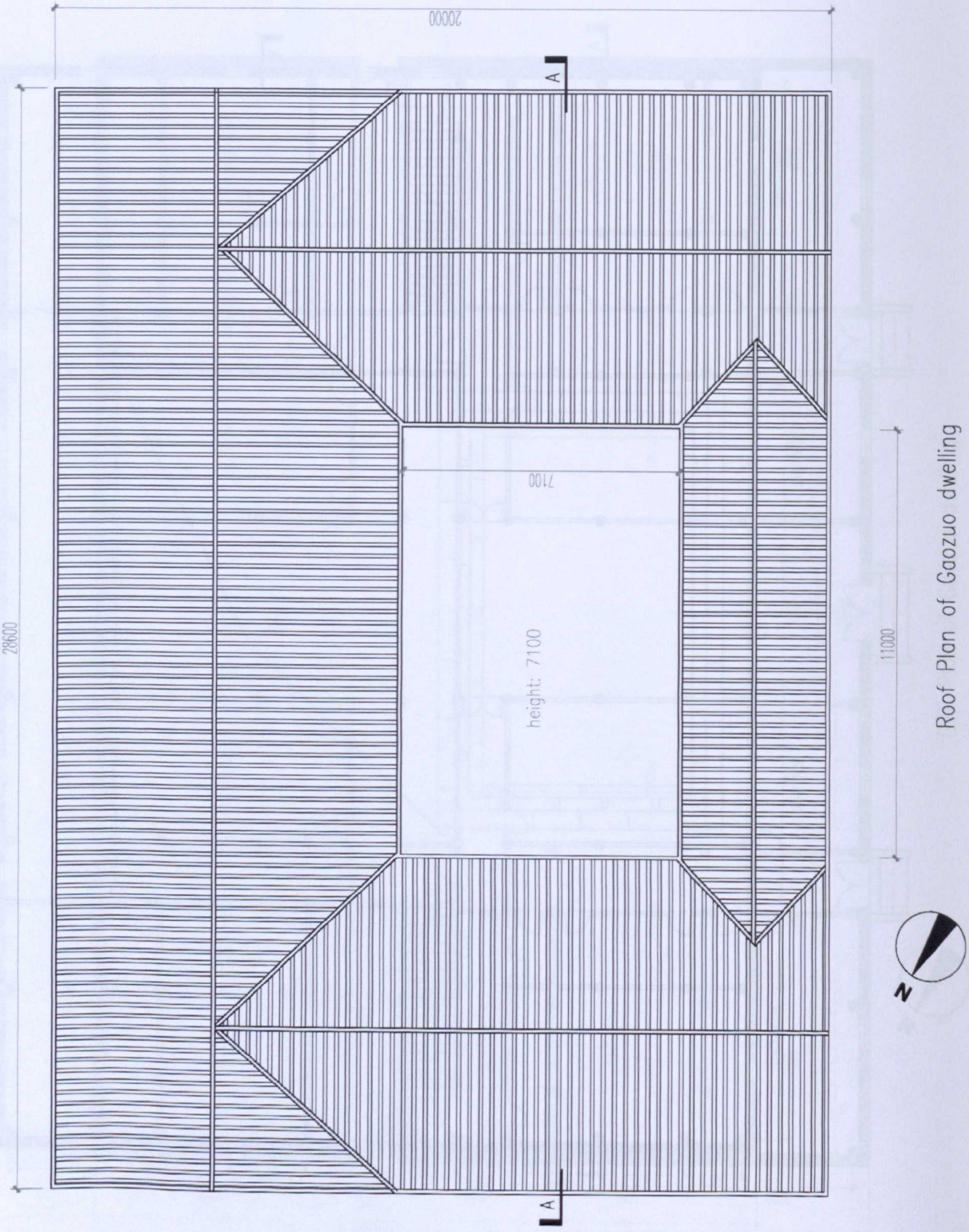
Section of Shuting dwelling



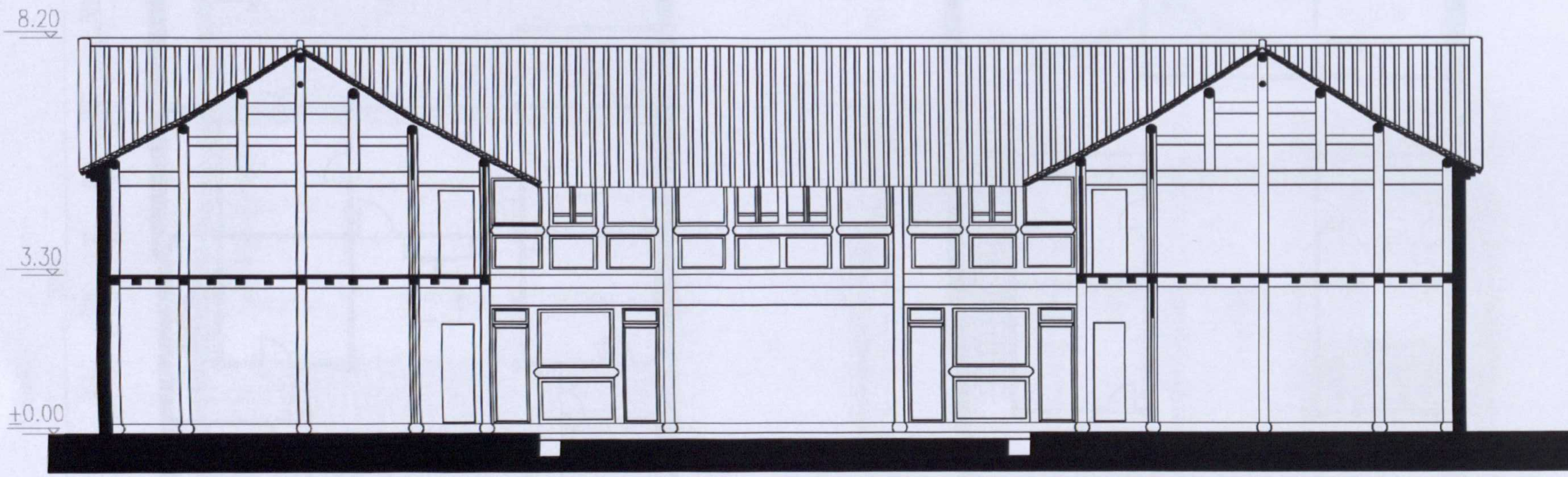
G/F Plan of Gaozuo dwelling



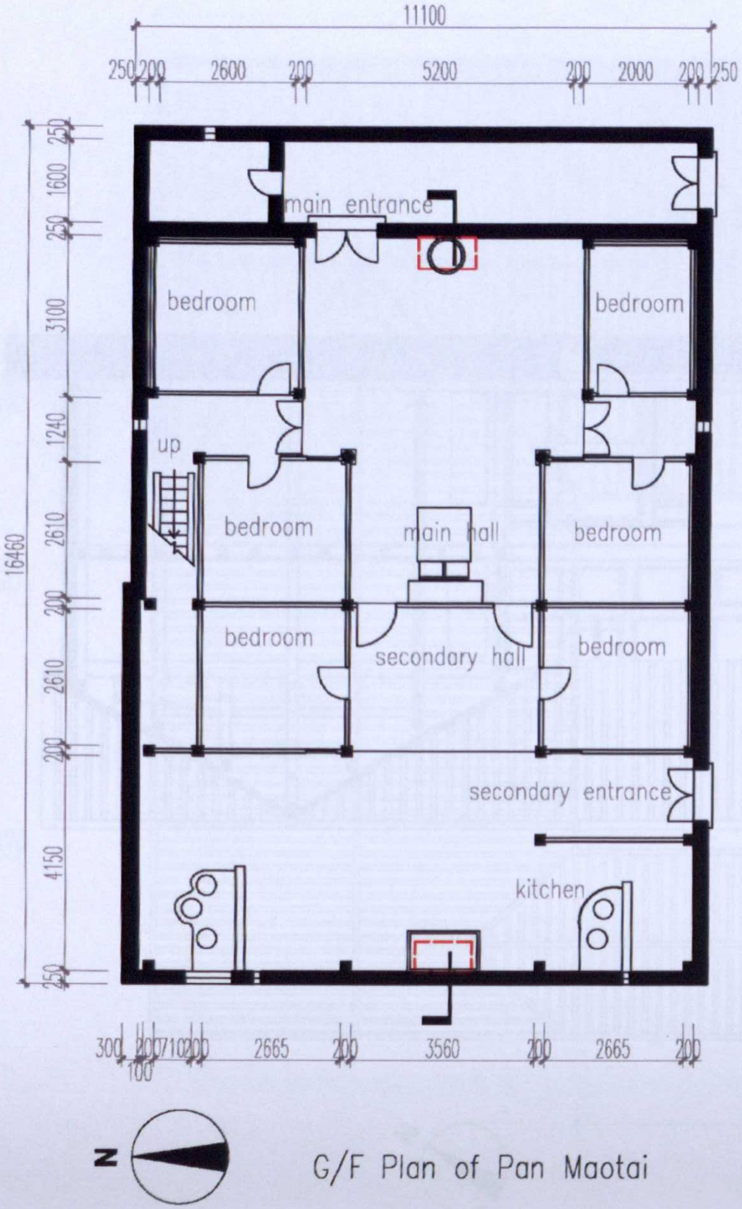
1/F Plan of Gaozuo dwelling



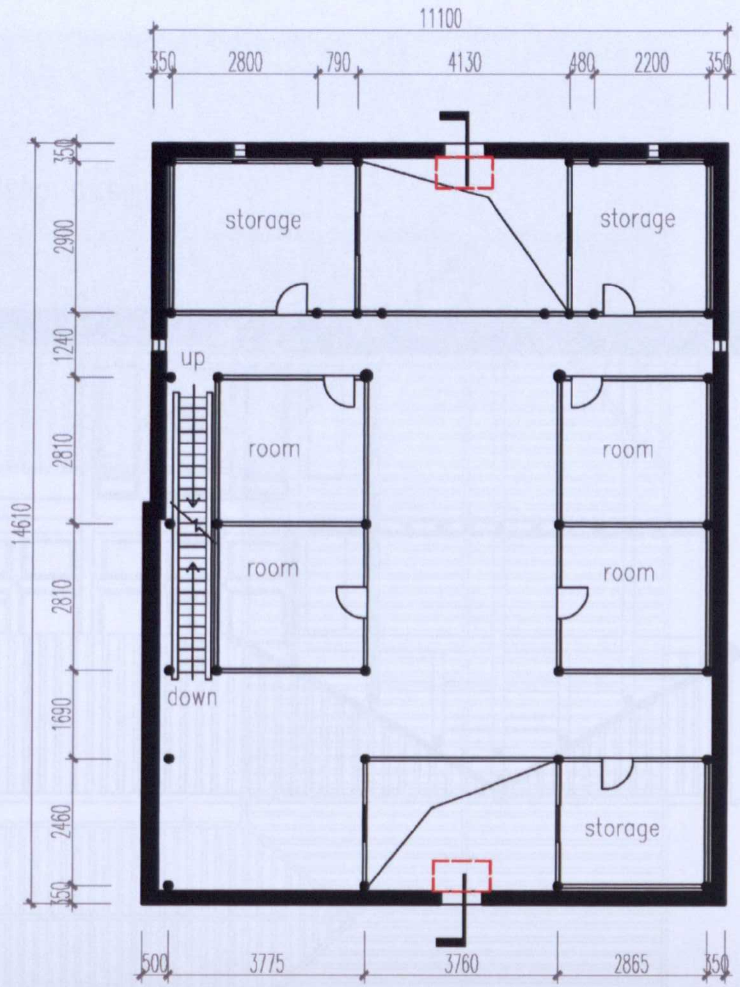
Roof Plan of Gaozuo dwelling



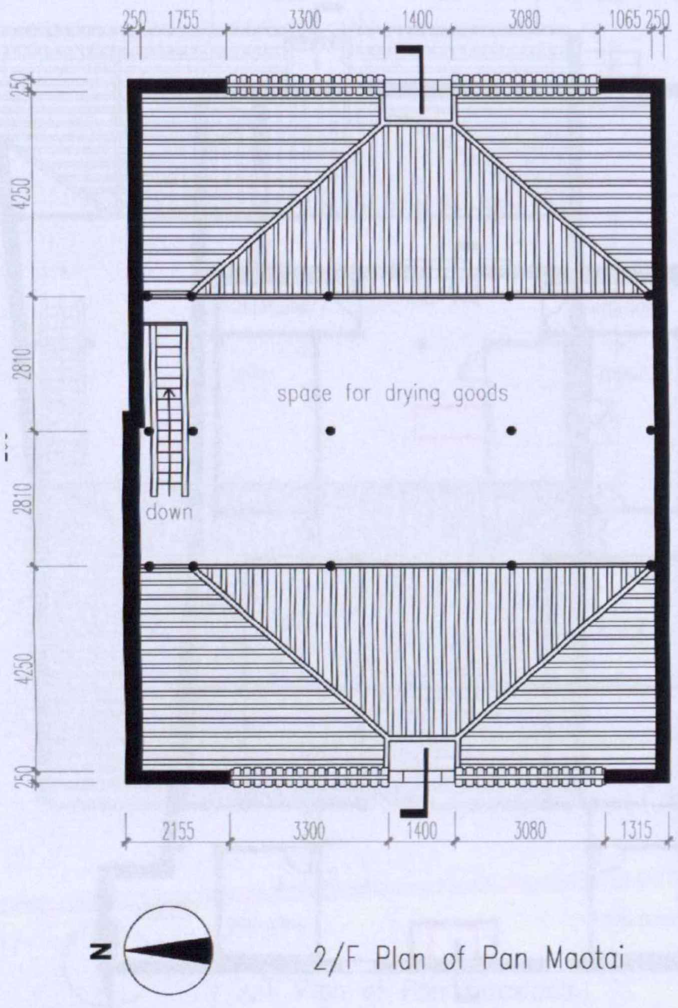
Section of Gaozuo dwelling



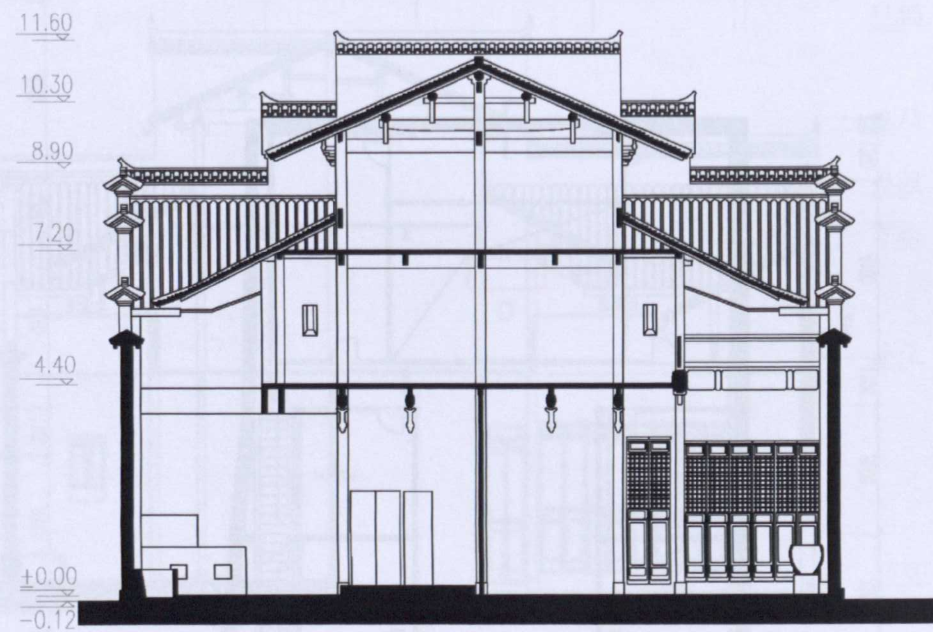
G/F Plan of Pan Maotai



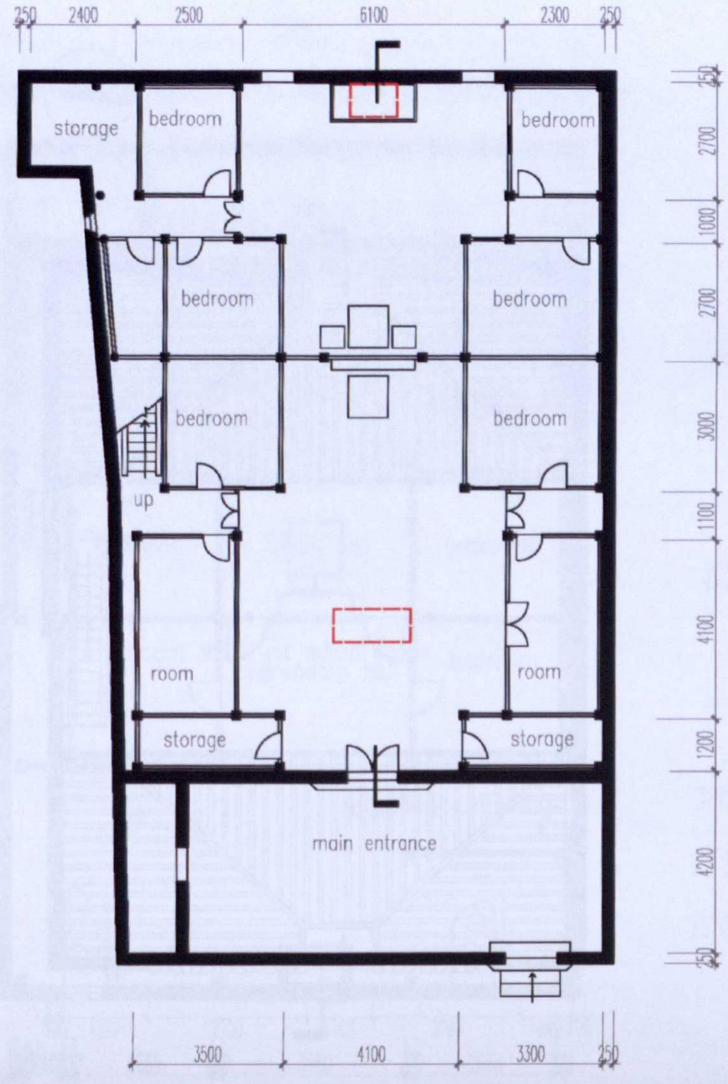
1/F Plan of Pan Maotai



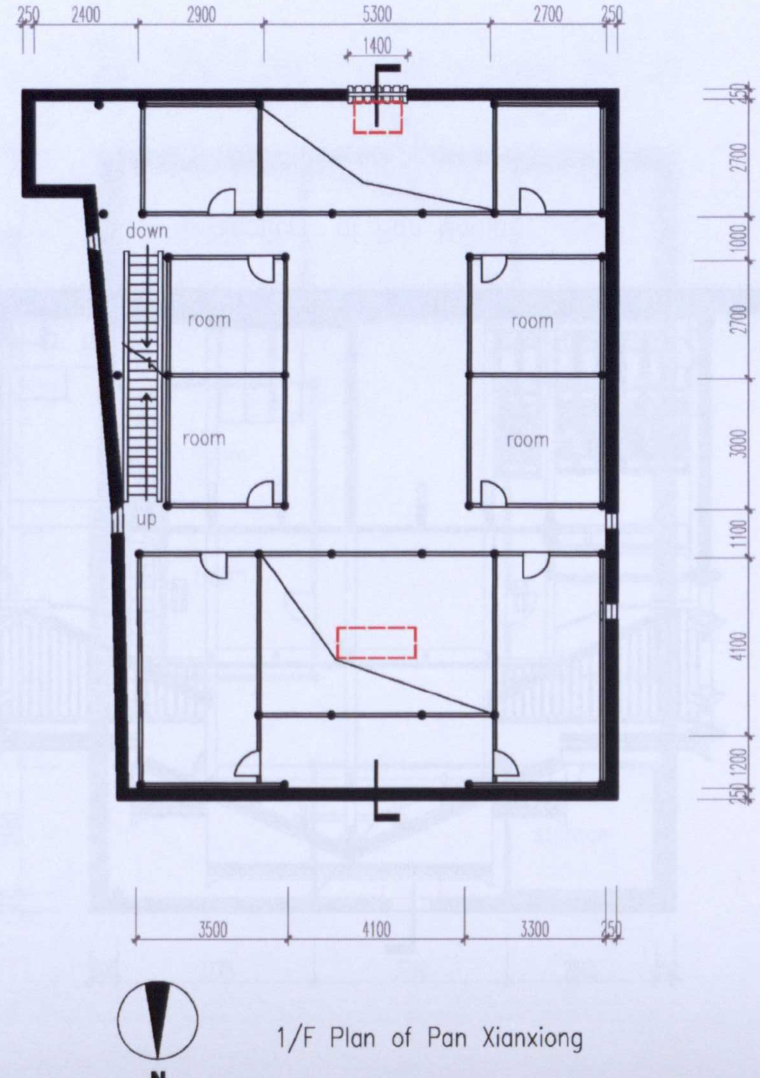
2/F Plan of Pan Maotai



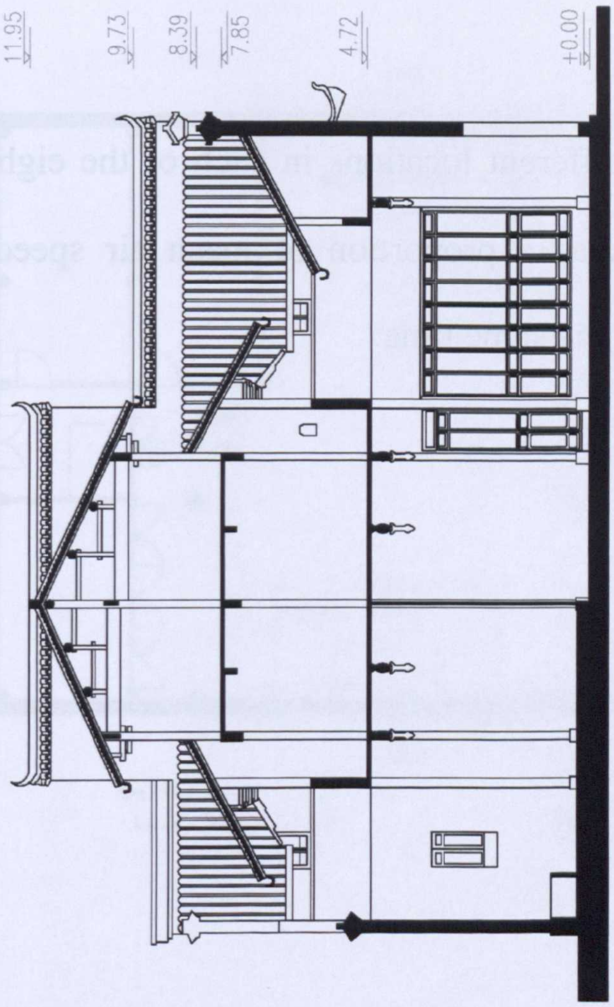
Section of Pan Maotai



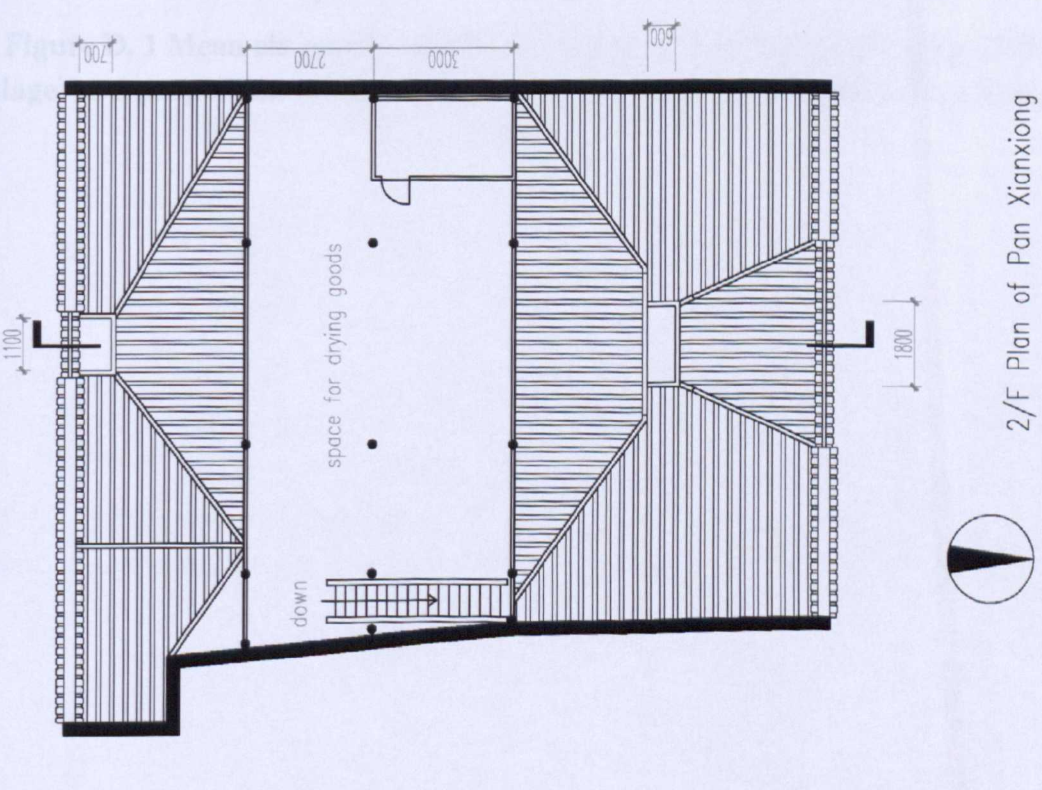
G/F Plan of Pan Xianxiong



1/F Plan of Pan Xianxiong



Section of Pan Xianxiong



2/F Plan of Pan Xianxiong

APPENDIX D

Mean air speeds at different locations in each of the eight Chinese vernacular dwellings as a proportion of mean air speed in main entrance measured at the same time

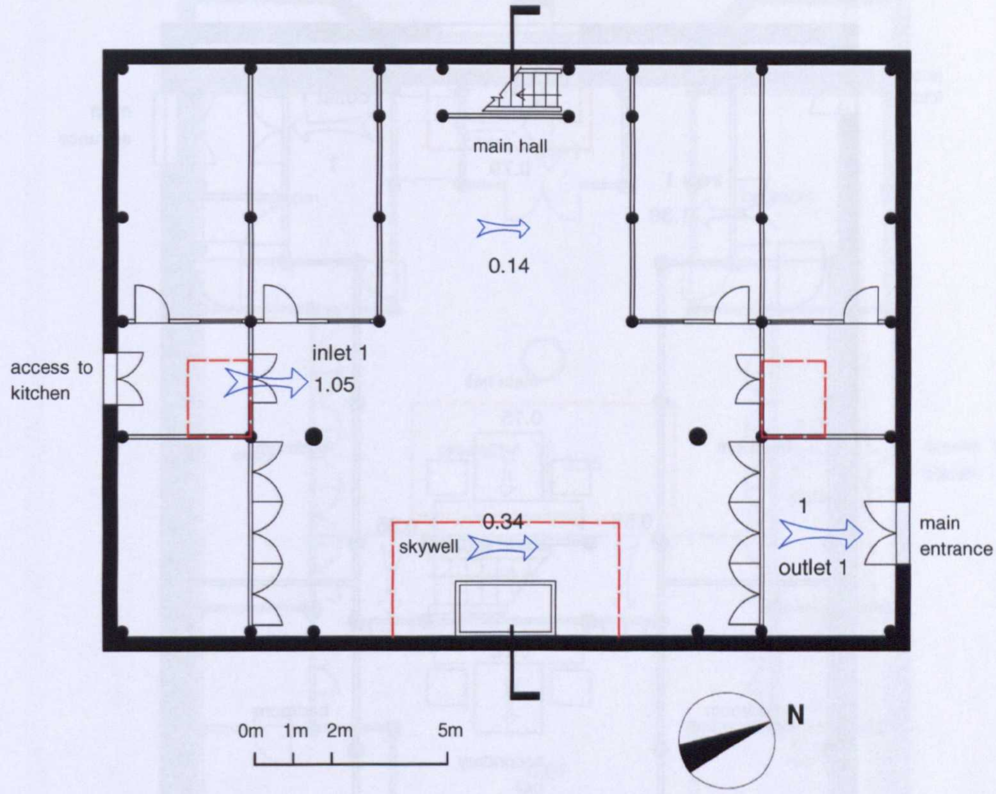


Figure D. 1 Mean air speeds at different points in the Dunren dwelling (Xidi village) as a proportion of mean air speed in main entrance measured at the same time

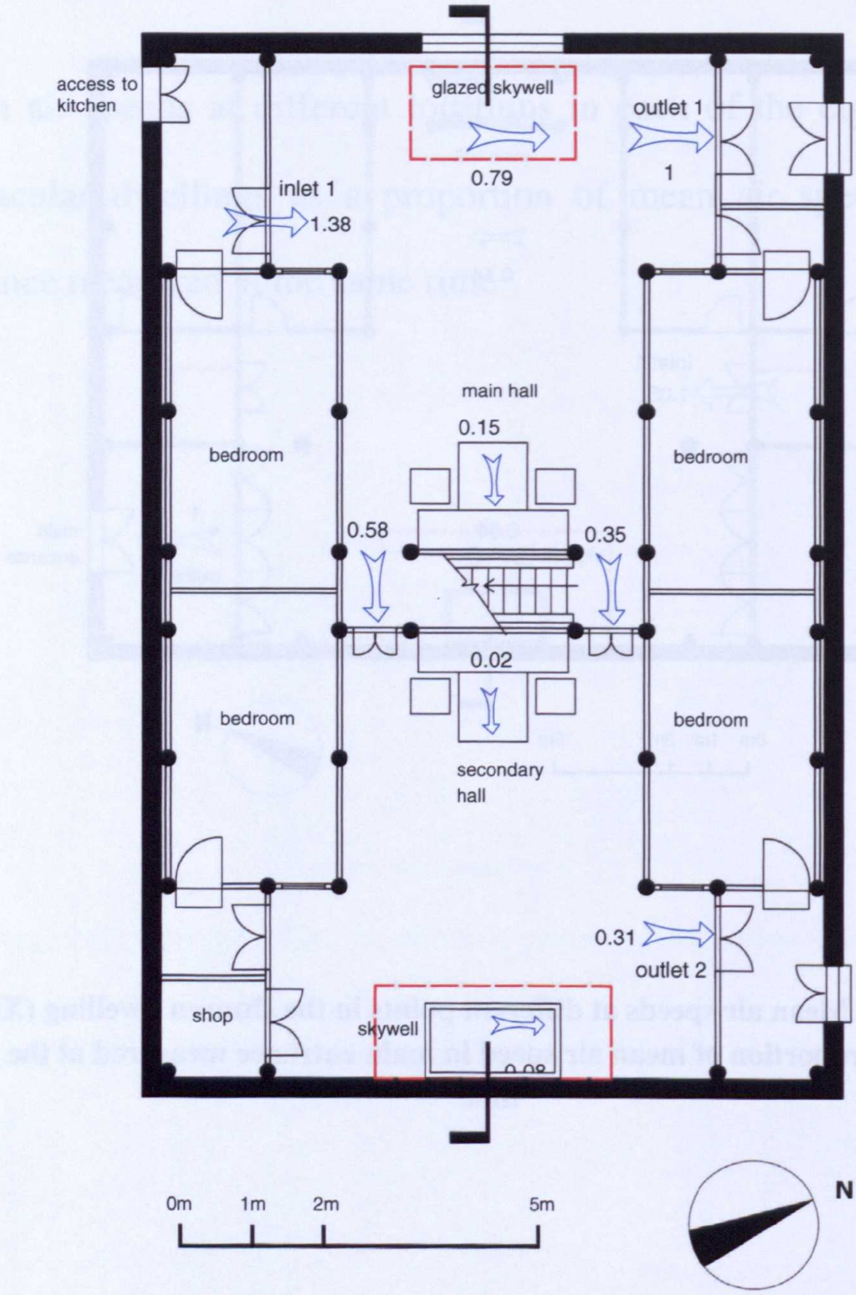


Figure D. 2 Mean air speeds at different points in the Lufu dwelling (Xidi village) as a proportion of mean air speed in main entrance measured at the same time

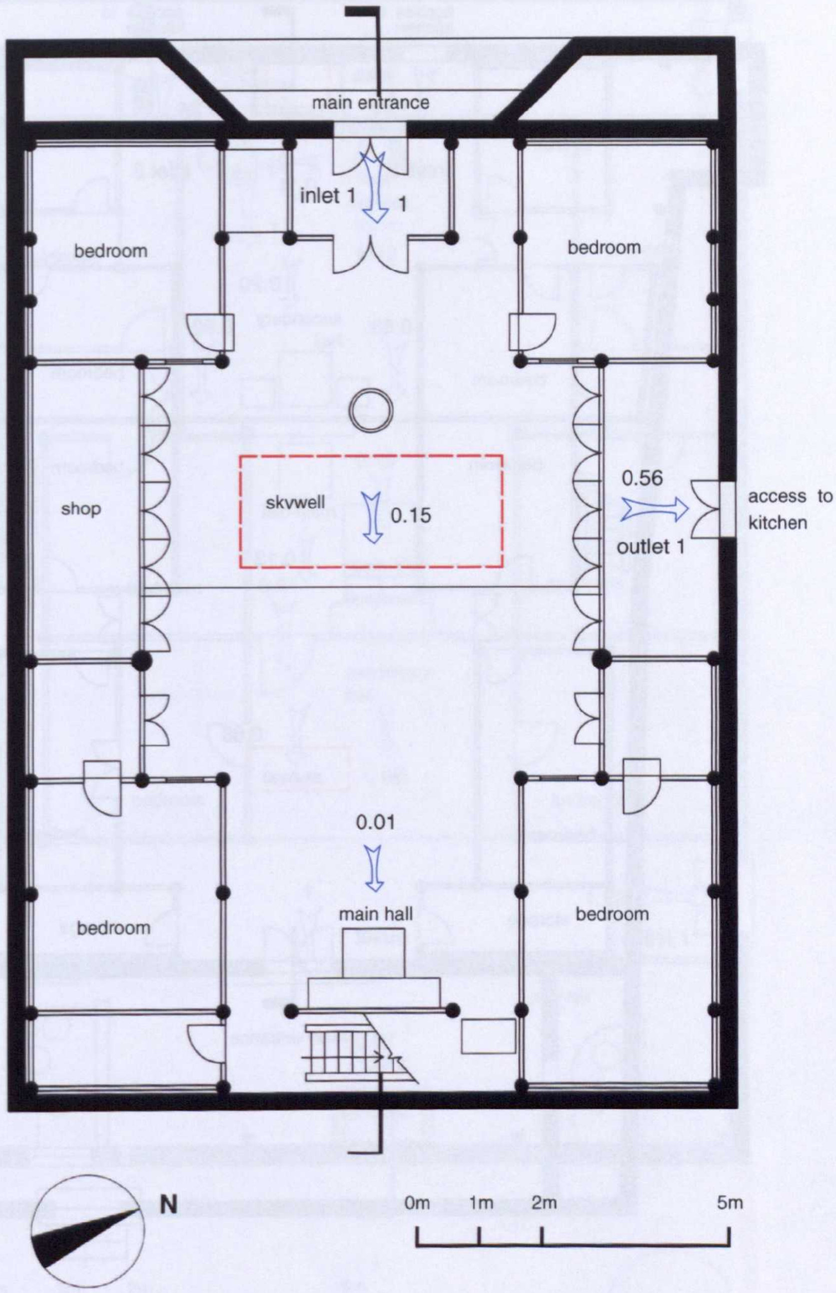


Figure D. 3 Mean air speeds at different points in the Yingfu dwelling (Xidi village) as a proportion of mean air speed in main entrance measured at the same time

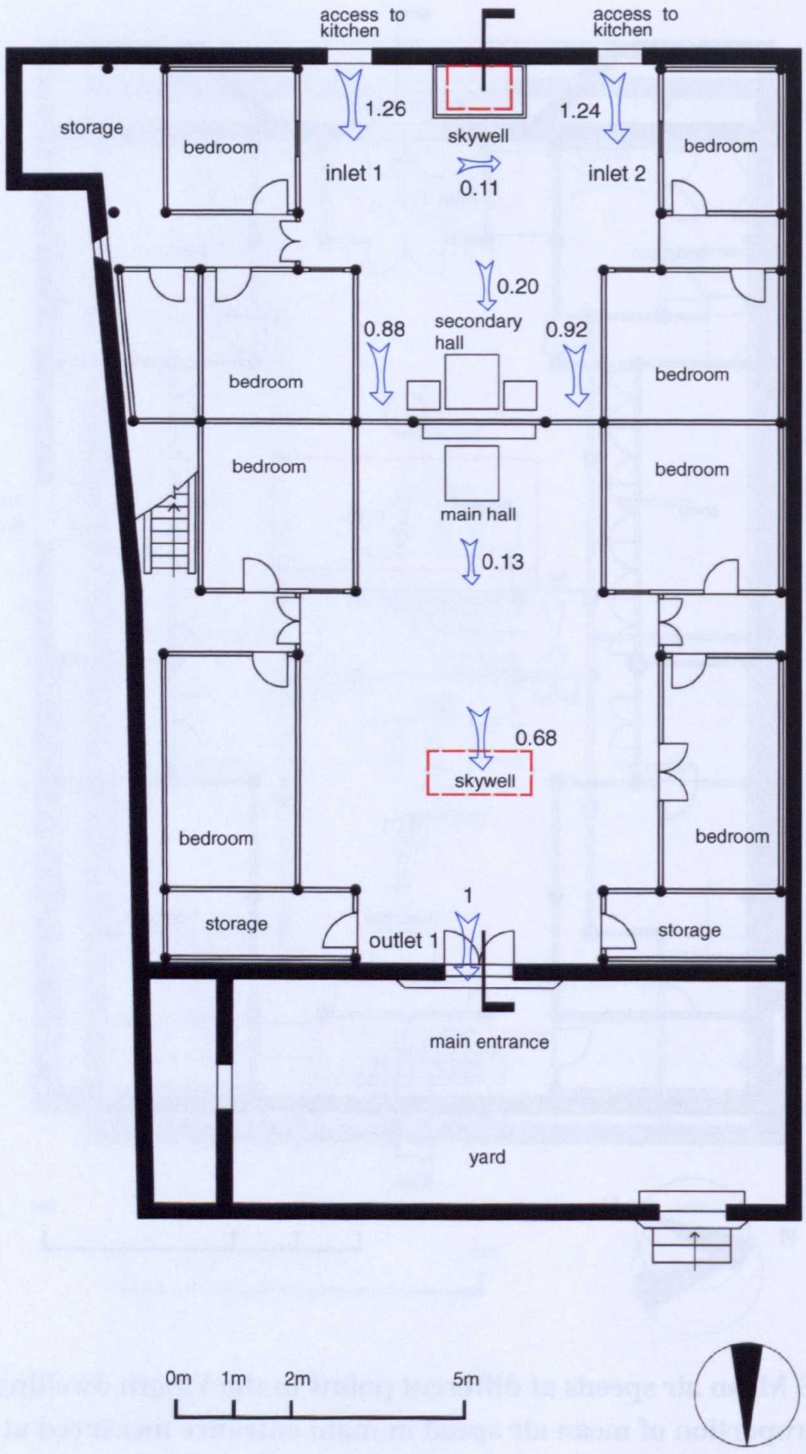


Figure D. 4 Mean air speeds at different points in the Panxianxiong dwelling (Zhifeng village) as a proportion of mean air speed in main entrance measured at the same time

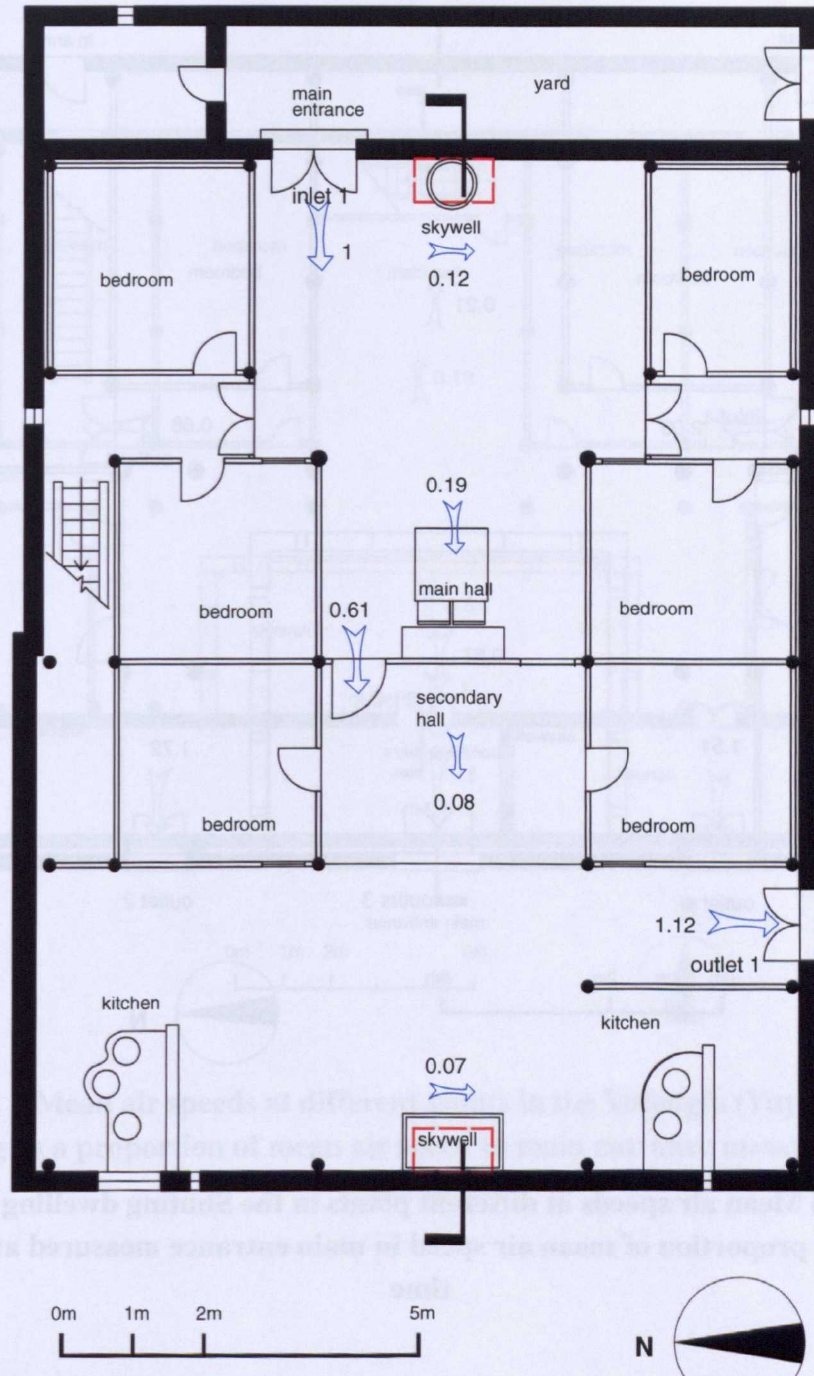


Figure D. 5 Mean air speeds at different points in the Panmaotai dwelling (Zhifeng village) as a proportion of mean air speed in main entrance measured at the same time

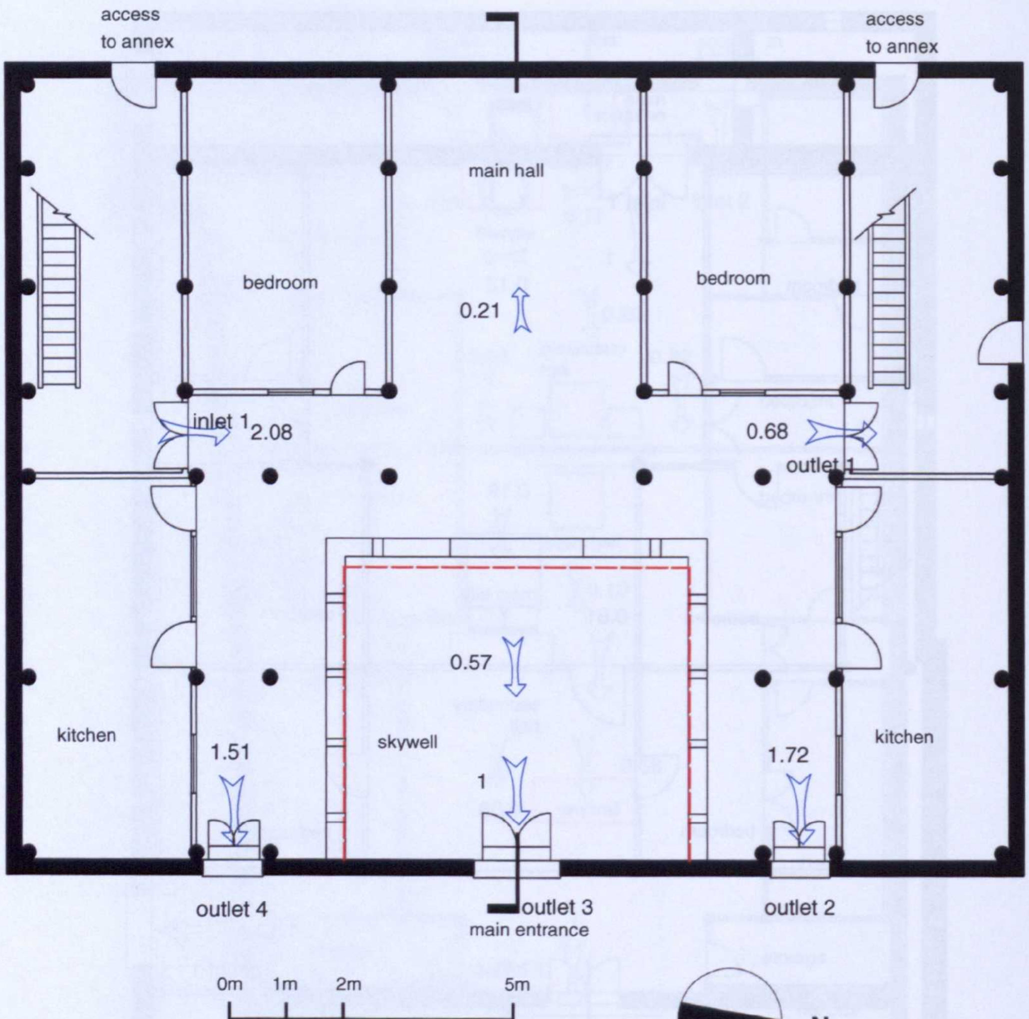


Figure D. 6 Mean air speeds at different points in the Shuting dwelling (Yuyuan village) as a proportion of mean air speed in main entrance measured at the same time

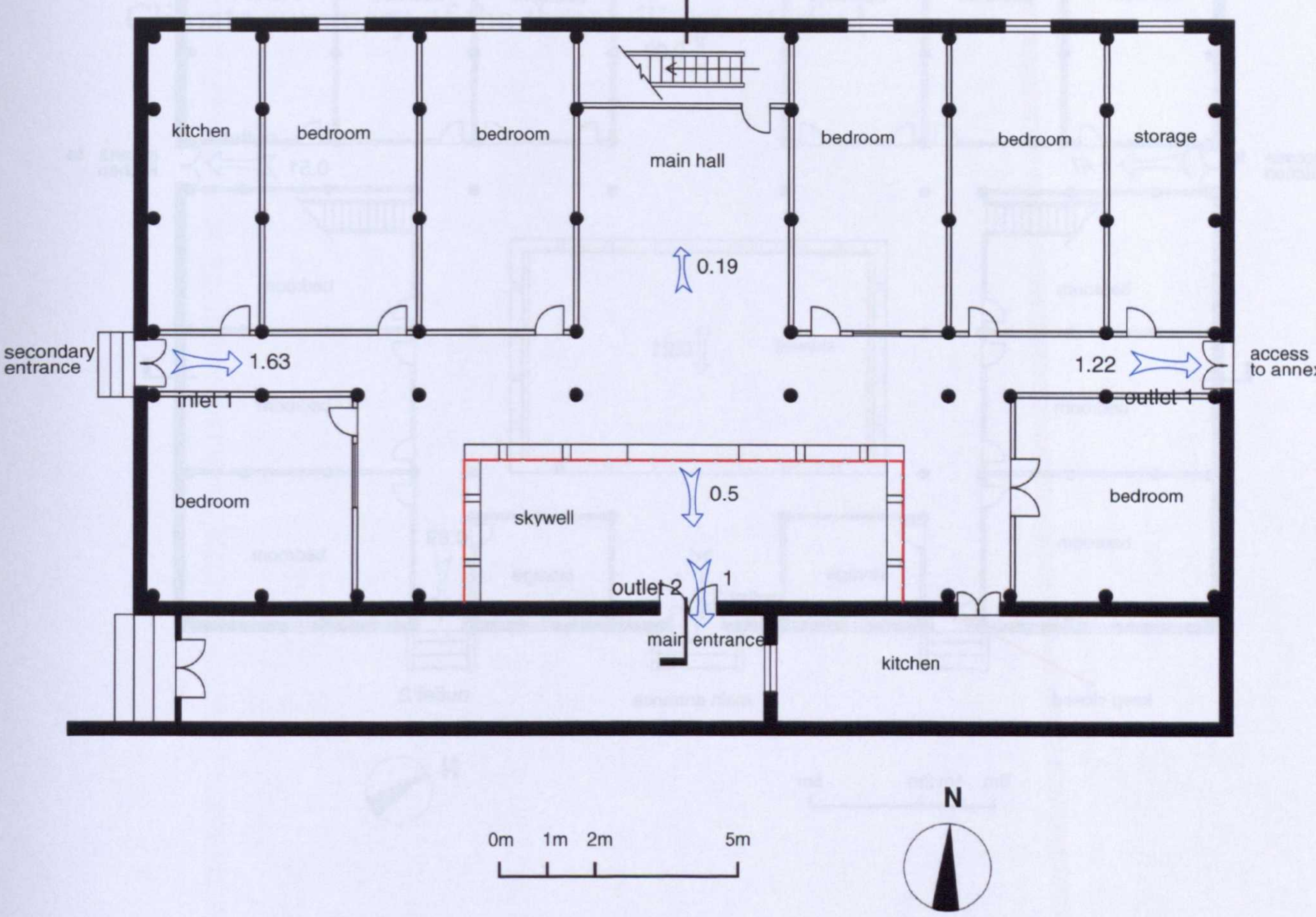


Figure D. 7 Mean air speeds at different points in the Yufengfa (Yuyuan village) dwelling as a proportion of mean air speed in main entrance measured at the same time

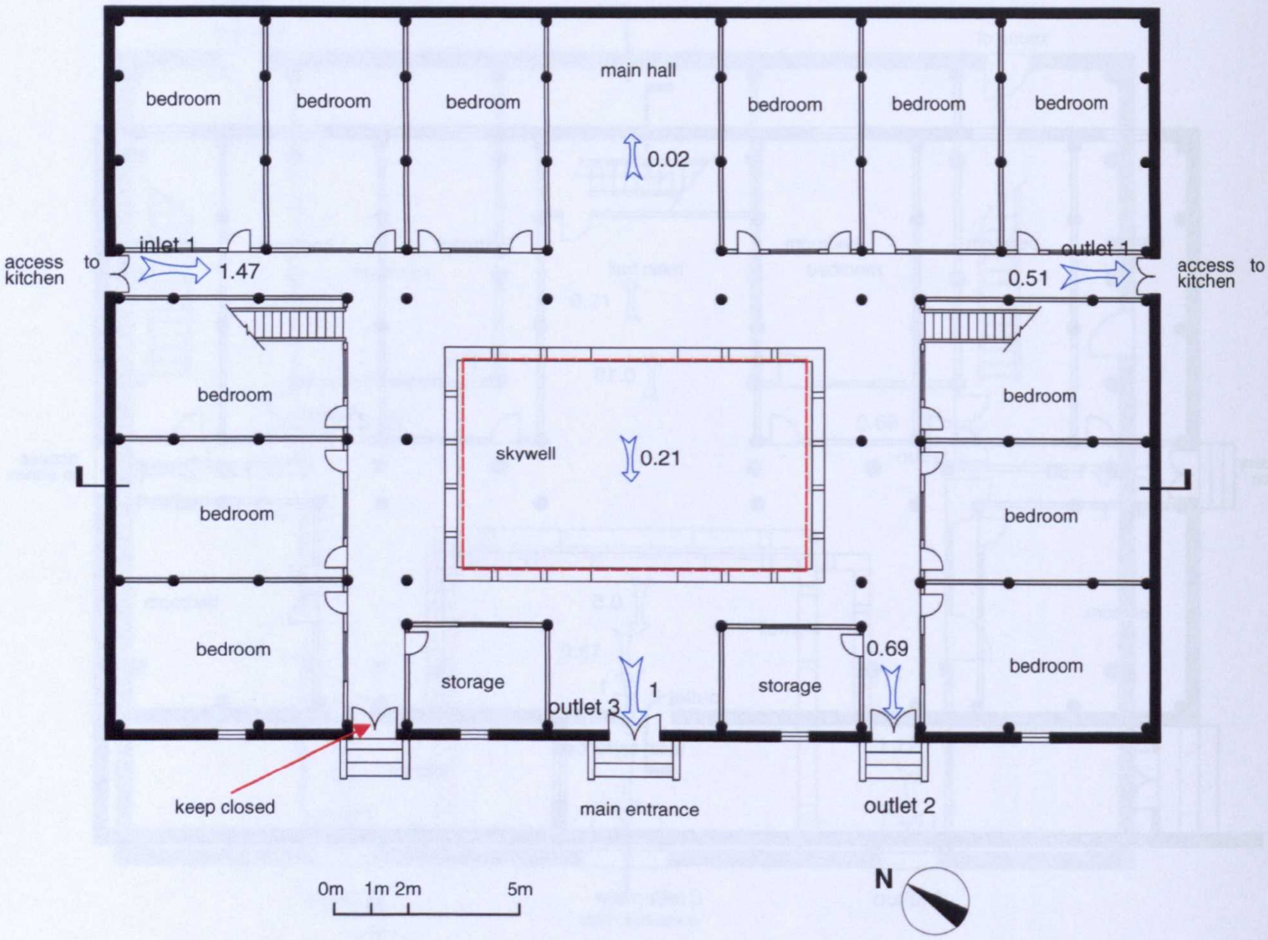
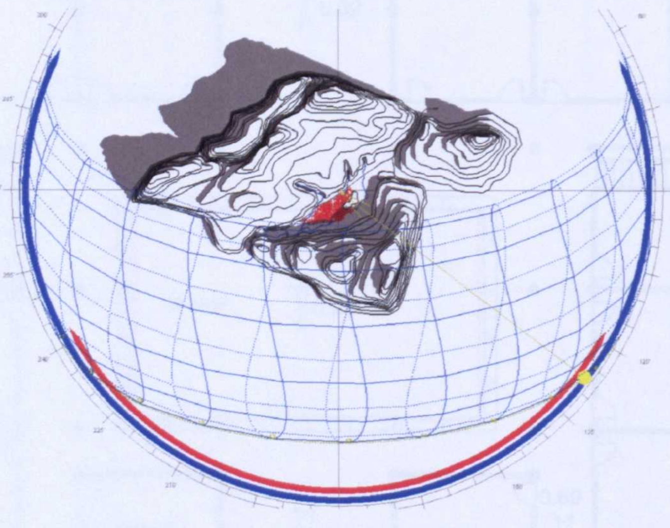


Figure D. 8 Mean air speeds at different points in the Gaozuo dwelling (Yuyuan village) as a proportion of mean air speed in main entrance measured at the same time

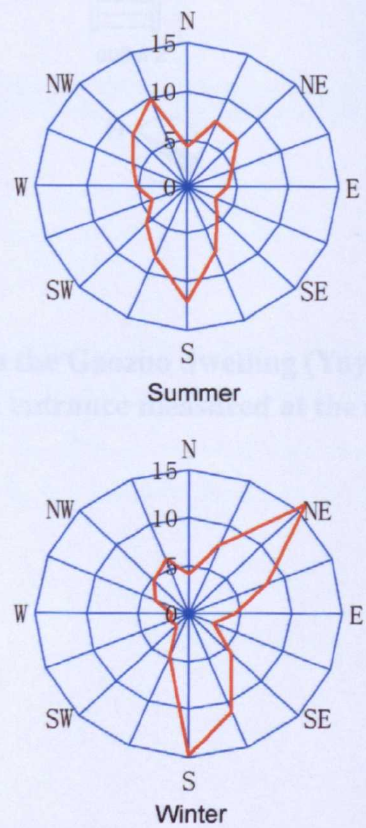
APPENDIX E

Climate summary of the three villages studied

Climatic summary of Xidi village



Sun path in Xidi village



Summer and winter prevailing wind in Xidi village

Spring (March to May)

Mild and Humid

average temperature: 16°C

max/min. temperature: 30.0°C /1.0°C

average relative humidity at 9am: 82%

average relative humidity at 3pm: 59%

prevailing wind: south

Summer (June to August)

Hot and Humid

hottest month: July (avg. 29.6°C)

average temperature: 28°C

maximum temperature: 35.8°C

average relative humidity at 9am: 82%

average relative humidity at 3pm: 62%

prevailing wind: northwest and south

maximum wind speed: 9.6m/s

Autumn (September to November)

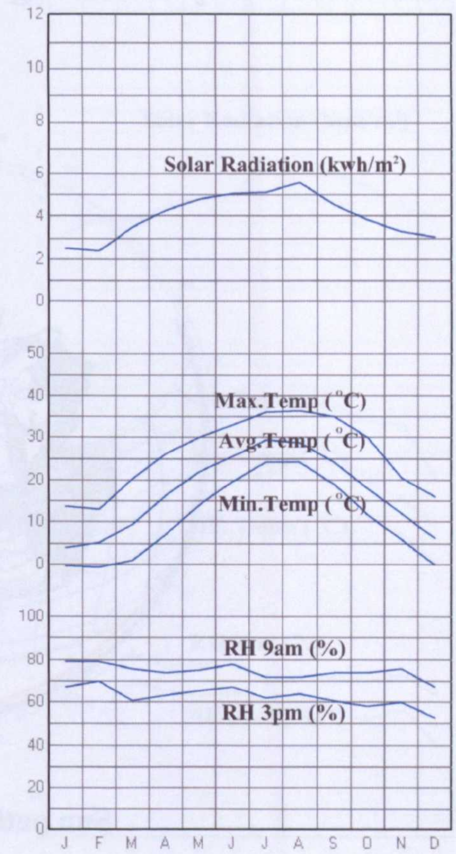
Warm and Humid

average temperature: 18.2°C
max/min. temperature: 35.1°C /6°C
average relative humidity at 9am: 86%
average relative humidity at 3pm: 52%
prevailing wind: southeast and northwest

Winter (December to February)

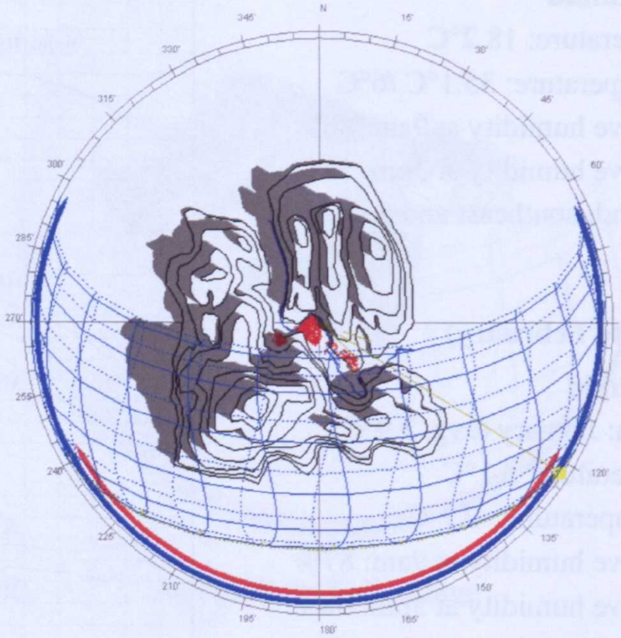
Cold and Humid

coldest month: January (avg. 3.9°C)
average temperature: 5.1°C
minimum temperature: -0.7°C
average relative humidity at 9am: 87%
average relative humidity at 3pm: 58%
prevailing wind: northeast and south
maximum wind speed: 11m/s

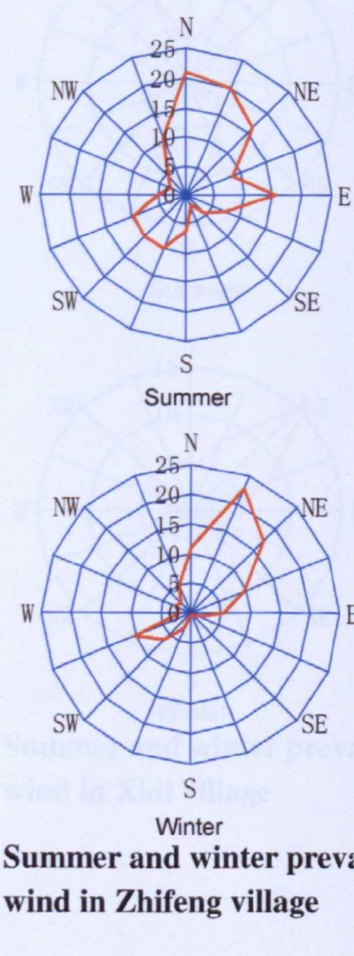


Climate summary of Xidi village

Climatic summary of Zhifeng village



Sun path in Zhifeng village



Summer and winter prevailing wind in Zhifeng village

Spring (March to May)

Mild and Humid
average temperature: 16.5°C
max/min. temperature: 29.8°C /0.8°C
average relative humidity at 9am: 79%
average relative humidity at 3pm: 67%
prevailing wind: west

Summer (June to August)

Hot and Humid
hottest month: July (avg. 29.0°C)
average temperature: 27.7°C
maximum temperature: 36.6°C
average relative humidity at 9am: 73%
average relative humidity at 3pm: 63%
prevailing wind: north and northeast
maximum wind speed: 8.7m/s

Autumn (September to November)

Warm and Humid

average temperature: 18.9°C

max/min. temperature: 34.6°C /5.9°C

average relative humidity at 9am: 72%

average relative humidity at 3pm: 56%

prevailing wind: south and east

Winter (December to February)

Cold and Humid

coldest month: January (avg. 4.9°C)

average temperature: 6.6°C

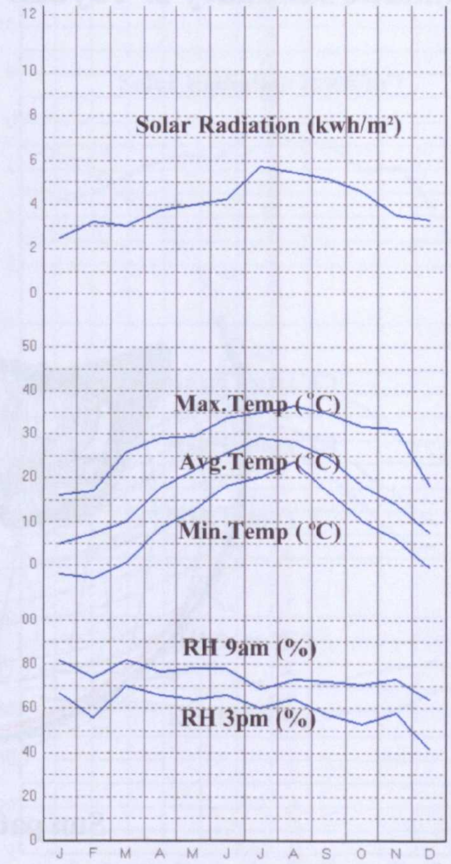
minimum temperature: -3°C

average relative humidity at 9am: 73%

average relative humidity at 3pm: 55%

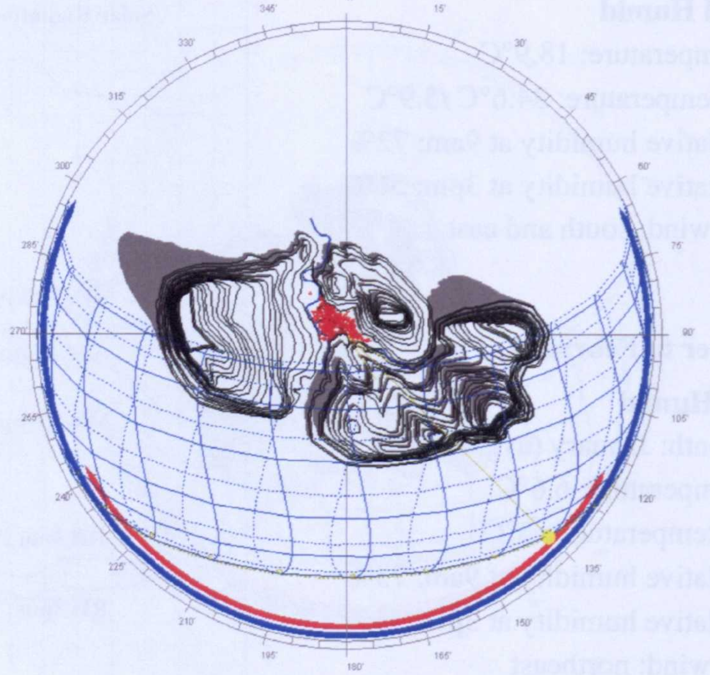
prevailing wind: northeast

maximum wind speed: 10m/s

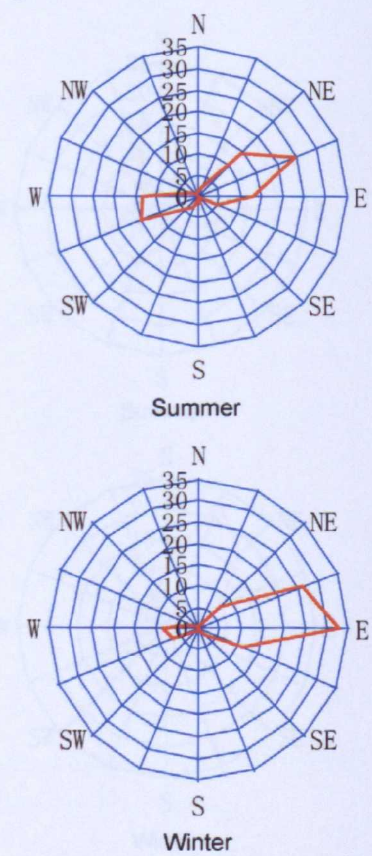


Climate summary of Zhifeng village

Climatic summary of Yuyuan village



Sun path in Yuyuan village



Summer and winter prevailing wind in Yuyuan village

Spring (March to May)

Mild and Humid

average temperature: 17.1°C
max/min. temperature: 31.5°C /3.4°C
average relative humidity at 9am: 76%
average relative humidity at 3pm: 64%
prevailing wind: east

Summer (June to August)

Hot and Humid

hottest month: July (avg. 28.5°C)
average temperature: 27.2°C
maximum temperature: 36.4°C
average relative humidity at 9am: 76%
average relative humidity at 3pm: 65%
prevailing wind: northeast and southwest
maximum wind speed: 9.4m/s

Autumn (September to November)

Warm and Humid

average temperature: 18.7°C

max/min. temperature: 34.3°C /4.1°C

average relative humidity at 9am: 75%

average relative humidity at 3pm: 60%

prevailing wind: southeast

Winter (December to February)

Cold and Humid

coldest month: January (avg. 5.1°C)

average temperature: 6.5°C

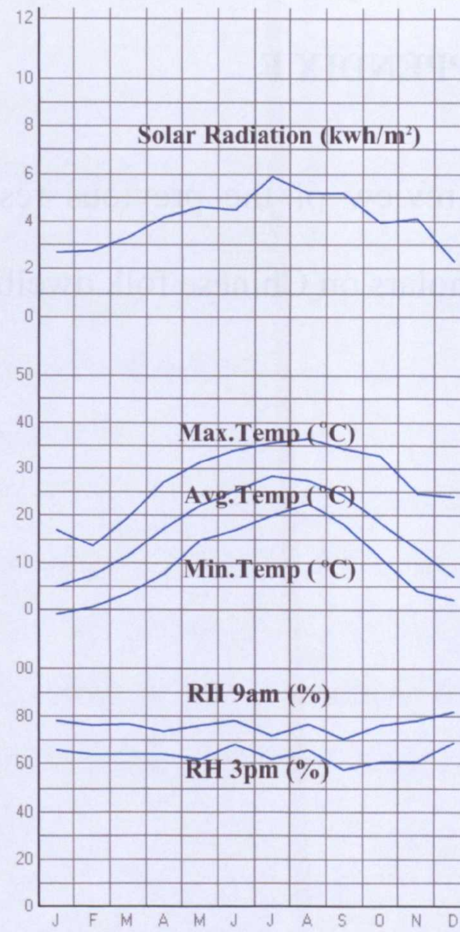
minimum temperature: -0.8°C

average relative humidity at 9am: 75%

average relative humidity at 3pm: 66%

prevailing wind: east and northeast

maximum wind speed: 10m/s



Climate summary of Yuyuan village

APPENDIX F

A review of the previous research done by Chinese and western scholars on Chinese folk dwellings

Research by Chinese scholars

Academic study of China's significant monumental architecture began in the 1920s under the leadership of Liang Sicheng and Liu Dunzhen, who were pioneers of the study of Chinese architectural history. These authors surveyed monuments such as temples, halls, pagodas, tombs, gardens, and bridges in the 1930s and 1940s (Knapp, 2000). Their studies did not extend to the traditional dwellings which were inhabited by ordinary people, and which reflect the manner in which those people lived. In 1930 Zhu Qiqian, founder and first president of the Society for Research in Chinese Architecture, stressed the importance of Chinese dwellings in his inaugural address (Zhu, 1930; Knapp, 1999). In the Society's quarterly bulletin, *Zhongguo yingzao xueshe huikan* (Bulletin of the Society for Research into Chinese Architecture), there are some observations and photographs of ordinary dwellings in remote villages and many detailed articles on monumental architecture.

Perhaps the first academic article about Chinese folk dwellings was a brief report by Long Feiliao, published in the Bulletin of the Society for the Research in Chinese Architecture in 1934 (Knapp, 2000). This report is an account of research on cave dwellings based on archaeological excavations and examination of existing cave dwellings (Long, 1934).

Japanese forces attacked China in 1937. In the years of inter-state and civil war that followed, much research into Chinese folk architecture was lost and never published. A few articles were published in the Society's bulletin in which the richness of vernacular dwellings in southwest China was highlighted (Knapp, 2000). In 1941, Liu Zhiping conducted a survey of some 200 folk dwellings in western Sichuan and provided detailed drawings of more than sixty of these. Publication of Liu's manuscript was prevented by the war. After the foundation of the People's Republic of China in 1949, Liu, as a junior associate to Liang Sicheng at Qinghua University, reorganised his manuscript under the title of *Residential Architecture of Sichuan.* In 1957, Liu's comprehensive account of the forms of Chinese architecture *Zhongguo jianzhu leixing ji jiegou* (Chinese Architectural Types and Structure) was published (Liu, 1957). It was not until 1990 that Liu Zhiping's Sichuan manuscript was published as an appendix to his book *Zhongguo juzhu jianzhu jianshi - chengshi, zhuzhai, yuanlin* (A Brief History of Chinese Residential Architecture – Cities, Houses, Gardens) (Liu, 1990).

In 1957, Liu Dunzhen published *Zhongguo zhuzhai gaishuo* (Introduction to Chinese Dwellings) which was considered to be a groundbreaking book. This book gave a brief historical account of the development of the Chinese dwellings from Neolithic times to the Qing dynasty. He classified Chinese folk dwellings into nine categories according to their plans and shapes – circular dwellings, longitudinal rectangular houses, transverse rectangular houses, L-shaped dwellings, three-in-one courtyard houses, four-in-one courtyard houses, mixed of three-in-one and four-in-one courtyard houses, donut-shaped dwellings and cave dwellings (Liu, 1957). With useful measured drawings and photographs, the book provides an assessment of building types as well as a description of vernacular dwellings. Its emphasis is morphological rather than historical. Despite its great merit, the book must be regarded as a preliminary work. The author considered that a nationwide survey needed to be undertaken to describe folk architecture in China comprehensively (Liu, 1957). While the traditional houses of particular areas have been studied, no single comprehensive survey of vernacular architecture in the whole of China has yet been carried out. Survey coverage remains uneven.

In 1957, in addition to the publication of Liu Zhiping's book on architectural types and structural forms, and Liu Dunzhen's book on Chinese dwellings, Zhang Zhongyi's book *Huizhou Mingdai zhuzhai* (Ming Dynasty Houses in Huizhou) was published following a survey of Ming dynasty domestic dwellings in She County, Jixi County and Xiuning County (Duan *et al.*, 2006). In this book the authors considered the dwellings of wealthy merchants of southern Anhui province. They provided a detailed record of these vernacular dwellings in which they incorporated descriptions of master plans, building plan type, façade appearance, structure and decoration (Zhang, 1957). With numerous original drawings and photographs, this book is still an outstanding reference work on these two to three centeries-old dwellings, many of which have been destroyed over the past fifty years.

Between 1956 and 1964, fieldwork was carried out by Chinese architects in order to document, survey, and assess common dwellings as well as the more opulent dwellings of gentry and merchants. During this period, about twenty articles on vernacular dwellings were published in *Jianzhu xuebao* (Architectural Journal). However this research only dealt with structural and spatial elements of the dwellings; very little attention was paid to the influence of historical, cultural, environmental and social factors in the formation of vernacular houses (Lu, 1996).

The Great Proletarian Cultural Revolution started in 1966 and lasted ten years. During this time research work in China could neither be conducted nor published. Under the leadership of Liu Dunzhen, *Zhongguo gudai jianzhu shi* (The History of Ancient Architecture) was drafted between 1959 and 1965. However, it was not until 1984 that this book was published, when the changed political environment in China made this possible. This book shows the development and the achievements of Chinese ancient architecture by citing a large number of historical documents and material records (Liu, 1984).

Once the Cultural Revolution ended in 1976, research into China's vernacular architecture gradually resumed. In the following two decades, the quality and quantity of publications about folk dwellings increased greatly (Knapp, 2000). A book by the Office for Research into Architectural History in the National Centre for the Development of Chinese Architecture and Technology, *Zhejiang minju* (Folk Dwellings of Zhejiang) was published in 1984; Zhejiang is especially rich in historically important vernacular houses. In this book the building materials and structure of folk dwellings as well as the social, historical, climatic and topographic contexts of their construction were examined. The book is supplementary to Liu Dunzhen's earlier nationwide surveys, and provides additional drawings and photographs (Centre for the Development of Chinese Architecture and Technology, 1984). *Yunnan minju* (Vernacular Dwellings of Yunnan) was produced by Yunnan Provincial Design Institute and published in 1986. This book describes the house forms of nine of the largest minority groups in Yunnan: Bai, Naxi, Hani, Yi, Dai, Jingpo, De'ang, Va and Lahu. Documentation and analysis of these dwellings was not the main purpose of writing this book. The aim of its authors was to investigate and adapt the existing house forms for use in modern construction (Yunnan Provincial Design Institute, 1986). *Fujian minju* (Vernacular Dwellings of Fujian) was published in 1987. In this book, settlement patterns, dwelling plans, building structure, construction materials and architectural details were surveyed in fifty locations around Fujian province. Nearly ninety individual houses were recorded in drawings and photographs in this book (Gao *et al.*, 1987)

According to Lu (1992), more than a hundred papers on Chinese vernacular houses had been published in a growing range of Chinese journals by the end of 1988 – journals including *Jianzhu xuebao* (Architectural Journal), *Jianzhu shi* (The Architect), *Jianzhu lishi yu lilun* (Architectural History and Theory), *Jianzhu shilun wenji* (Treatises on the History of Architecture), *Gu jian yuanlin jishu* (Technology of Ancient Architecture and Gardens), *Huazhong jianzhu* (Huazhong Architecture), *Xin jianzhu* (New Architecture), *Zhongguo gudai jianzhu shihua* (Historical Notes on

China's Ancient Architecture), and *Fujian jianzhu* (Architecture of Fujian).

As Chinese vernacular dwellings received increasing attention from researchers, the first National Conference on Traditional Houses was held in Guangzhou in November 1988. Professor Lu Yuanding of South China University of Technology's Department of Architecture presided over this meeting. The 1991 book *Zhongguo chuantong mingju yu wenhua* (China's Traditional Vernacular Dwellings and Culture) contains half of the papers presented at this conference (Lu *et al.*, 1991). These conference papers were not confined to the architecture of traditional houses, but also dealt with historical, cultural, linguistic, geographic and aesthetic topics (Knapp, 2000). Following this inaugural meeting large academic conferences on Chinese vernacular architecture have been held in China almost every year since 1990 (Knapp, 2000).

The 1991 book *Suzhou minju* (The Vernacular Dwellings of Suzhou) includes a spatial analysis of the ancient villages in Suzhou. Dwellings are classified simply as large, medium or small. The main components of Suzhou dwellings – entrance, entrance hall, waiting hall, main hall, family room, kitchen, courtyard and skywell are examined. The furniture of Suzhou houses is also discussed, as is dwelling configuration (Xu *et al.*, 1991).

Beijing *siheyuan*, also known as four-in-one courtyard or quadrangle houses, were the subject of books in the 1990s. Although many of the publications discussed earlier mentioned Beijing *siheyuan*, this typical Chinese domestic dwelling form had not been studied in depth until the late twentieth century. *Beijing jiucheng yu Ju'er hutong* (The Old City of Beijing and Ju'er Lane) and *Beijing siheyuan* (Beijing Courtyards) included examinations of the historical background of *siheyuan*. In the former book, Wu Liangyong and his colleagues describe their restoration of Ju'er Lane and proposed it as a model for the replacement of damaged single-storey *siheyuan* with modern multistoried structures built in traditional styles (Wu, 1994). Wu's book drew attention to the destruction of historic courtyard houses and their neighbourhoods and provided suggestions for more historically sensitive development of Beijing (Wu, 1994). *Beijing siheyuan* was a record of a survey of Beijing courtyard houses with an appendix providing a useful list of 102 historically important courtyard dwellings found within Beijing (Lu and Wang, 1996).

In the 1990s, after extensive fieldwork throughout China, a multi-volume collection of photographs documenting Chinese folk dwellings was published by Jiangsu Fine Arts Publishing House, under the general editorship of Zhu Chengliang. Eleven large volumes with black and white prints have been published – Southern Anhui by Yu Hongli (1993), The Jiangnan Canal Country by Zheng Guangfu (1993), Shanxi by Wang Qijun (1994), The Architecture of the Tujia Minority Nationality by Zhang Liangnie (1994), The Architecture of the Dong Minority Nationality by Chen Shouxiang (1996), and Beijing *Siheyuan* by Wang Qijun (1998). These works provide accurate and comprehensive descriptions of China's old houses, and contain numerous well-chosen photographs of high quality. They are an important resource in the study of Chinese vernacular architecture.

From 1992 to 1999, China's Southeast University conducted an extensive survey of Huizhou villages and domestic dwellings. Using the results of the survey, scholars such as Gong Kai and Shan Yong have compiled a series of books about the ancient villages in Huizhou – the villages of Zhanqi (Gong, 1996), Yuliang (Gong, 1998), Tangyue (Gong, 1999), Zhifeng (Gong, 1999) and Xiaoqi (Gong, 2001). Each book is concerned with a single village and describes in detail the village's location and development, the dwelling types present within the village, and the village's historical culture.

From 1990 to 2005, Chen Zhihua with his colleagues and his students from Tsinghua University carried out an extensive survey of rural architecture. More than ten ancient villages have been observed and recorded. A series of books under the overall title of *Zhonghua yichan – xiangtu jianzhu* (Chinese Heritage – Rural Architecture) has been published using material collected in these surveys. Each village's historical background and location are described; buildings in the village – classified as dwellings, educational buildings, shops and ancestral temples – are introduced and drawings of the buildings are supplied. The ornamentation and decoration of buildings are examined.

In 2006, Duan Jin and his colleagues at Southeast University published a book *Kongjian yanjiu 1: shijie wenhua yichan xidi gucunluo kongjian jiexi* (Urban Space Research 1: Spatial Analysis of Xidi Ancient Village – a World Heritage Site). This book records in detail the establishment, building design and urban space of Xidi village. Factors affecting the development of this village, including physical geography condition, geomancy, Confucian thought and clan tradition are analyzed. The relationships between individual buildings, groups of dwellings, street and village are investigated, and people's activities within these spaces are examined (Duan *et al.*, 2006).

Research by Western scholars

Westerners began to write about Chinese folk dwellings in the early twentieth century. Due to China's isolation from the rest of the world from the late 1940s to the late 1970s, it was difficult for any foreigner to carry out first-hand architectural investigation in China during this period. In 1947, an academic article *The Houses of the Chinese* appeared in Geographical Review. In this article Spencer (1947) argued that particular attention should be paid to the study of Chinese vernacular houses.

Using material from Chinese books and articles published in the 1950s, Boyd (1962) published *Chinese Architecture and Town Planning* to give a brief introduction to the main traditions in vernacular Chinese architecture and town planning. This book omits any discussion on twentieth century developments in Chinese architecture and its referencing of the original drawing and photographs produced by Chinese architects is deficient (Knapp, 2000).

Since the end of the Cultural Revolution in 1976, there has been a growing interest in Chinese domestic architecture on the part of American, European, and Japanese researchers. Using the structure of Liu Dunzhen's 1957 book *Introduction to Chinese Dwellings* as a basis, Knapp produced *China's Traditional Rural Architecture: A Cultural Geography of the Common House* in 1986. With nearly 200 photographs and drawings, this book is the first work in English in which the development, variety, construction techniques and social background of Chinese folk dwellings are examined. The book is intended as an introduction to the subject for Western readers (Knapp, 1986). The same author subsequently wrote *The Chinese House* - an even briefer introductory treatment for a general audience (Knapp, 1990). He also produced a book entitled *China's Vernacular Architecture: House Form and Culture* in 1989. Using buildings from the province of Zhejiang as examples, the author describes the natural environment, spatial elements, construction principles and techniques, exterior and interior ornamentation, and folk traditions associated with rural dwellings. The ways in which these elements are changing are considered (Knapp, 1989). Knapp's *China's Old Dwellings* includes detailed examination of plan and shape of Chinese dwellings, traditional timber framing systems and representative housing types northern, southern and western China (Knapp, 2000). Knapp's *Chinese Houses: The Architectural Heritage of a Nation* published in 2005 includes twenty case studies of houses in different parts of China. Among the types of houses covered by the book are the Beijing courtyard house, the Fujian five phoenix mansion, the Jiangsu canal House, the Shaanxi cave dwellings, the Guangdong Hakka rammed earth houses and the Sichuan U-shaped farmhouse. The book is illustrated with numerous architectural drawings and photographs of high quality (Knapp, 2005).

David Ping-Yee Lung published a bilingual Chinese/English book, *Chinese Traditional Vernacular Architecture*, in 1991. In this book, the dwellings are divided into eight types according to external form. Lung classifies houses as courtyard houses, cave dwellings, Hakka rammed earth houses, overhanging houses, stilt houses, flat-roof houses, tent dwellings and watch towers. The built heritage of Hong Kong – domestic houses, study halls, ancestral halls, markets and temples – is also surveyed and discussed (Lung, 1991).

In 1997, one of the most important books in global architectural research, the *Encyclopedia of World Vernacular Architecture*, edited by Paul Oliver, was published. More than 750 specialists from over 80 countries contributed to this three-volume work. Volume 1 describes theoretical approaches and concepts, while the second and third volumes document domestic architecture in seven continental areas and nearly 100 subzones. China is divided into northern and southern zones in this publication. Traditional dwellings from different Chinese provinces are discussed. Building materials, structure and building space are briefly introduced, as are the geographical, climatic and cultural backgrounds of the different houses (Oliver, 1997).

APPENDIX G

Propositions proved mathematically

The following propositions can be proved mathematically.

Proposition 1 When no source of illumination other than the opening of the skywell is present, the area immediately beneath a skywell is most strongly illuminated ($DF_{m,sky}$ has the highest value). Peak illuminance is at the mid-point of the skywell.

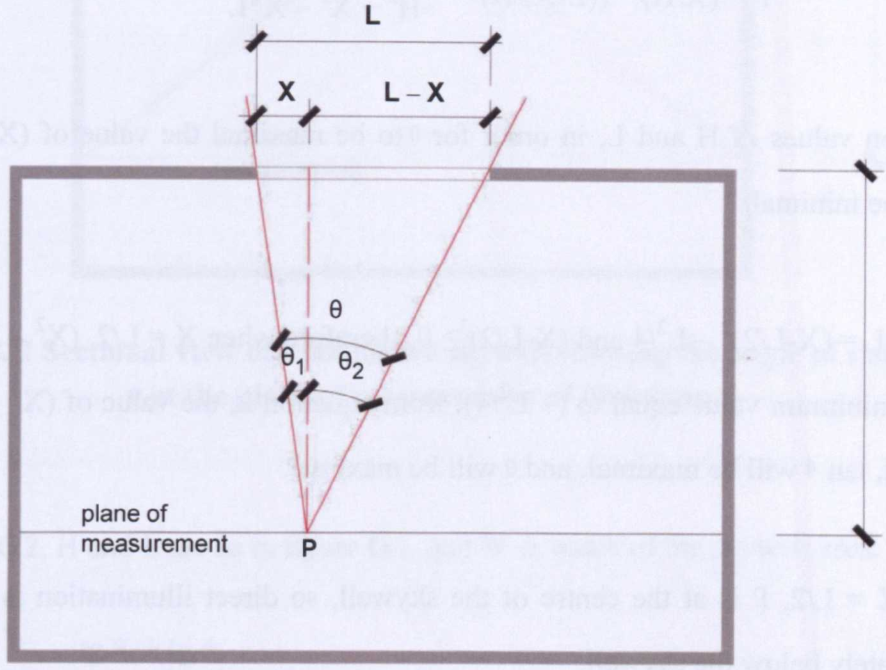


Figure G. 1 Sectional view of a simplified skywell showing the angle of visible sky θ at a point on a measurement plane above floor level

Consider a point P on a plane of measurement close to a skywell floor. In figure G.1, H represents the vertical distance between the plane of measurement and the skywell, while L represents the width or length of the skywell. Condider θ as the sum of two right-angled triangles θ_1 and θ_2.

$$\text{tg}\ \theta = \text{tg}\ (\theta_1 + \theta_2) = \frac{\text{tg}\ \theta_1 + \text{tg}\ \theta_2}{1 - \text{tg}\ \theta_1 * \text{tg}\ \theta_2} \qquad \text{eq.1}$$

$$\text{tg}\ \theta_1 = X/H$$

$$\text{tg}\ \theta_2 = (L\text{-}X)/H$$

$$\text{tg}\ \theta = \frac{X/H + (L\text{-}X)/H}{1 - (X/H) * ((L\text{-}X)/H)} = \frac{H*L}{H^2 + X^2 - X*L} \qquad \text{eq.2}$$

For given values of H and L, in order for θ to be maximal the value of $(X^2 - X*L)$ should be minimal.

$X^2 - X*L = (X\text{-}L/2)^2 - L^2/4$ and $(X\text{-}L/2)^2 \geq 0$; therefore when $X = L/2$, $(X^2 - X*L)$ will have a minimum value equal to $(- L^2/4)$; from equation 2, the value of $(X^2 - X*L)$ is minimal, tan θ will be maximal, and θ will be maximal.

When $X = L/2$, P is at the centre of the skywell, so direct illumination is strongest immediately below the skywell.

Proposition 2 For a skywell house, $DF_{m,uti}$ will be higher when the skywell is located centrally above the utility area than when it is located at the periphery of the utility area.

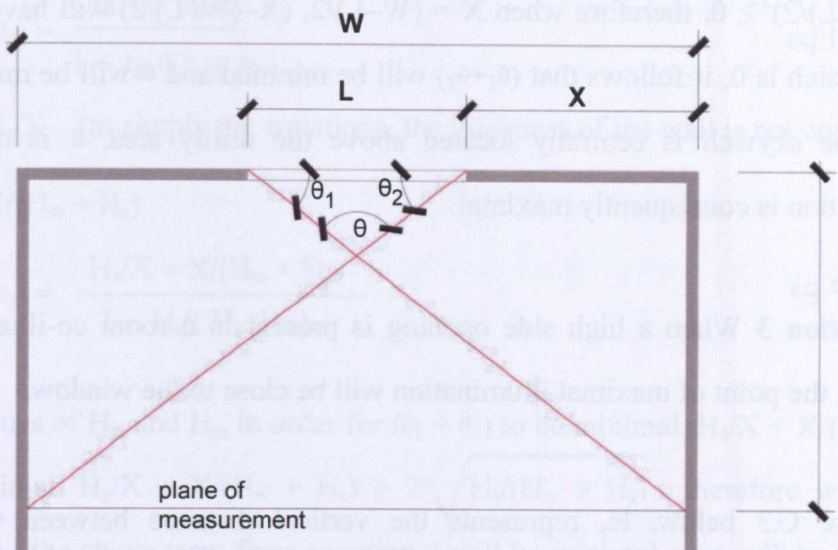


Figure G. 2 Sectional view of a simplified skywell showing the angle of visible sky θ at the plane of measurement of illuminance

In figure G.2, H and L are as in figure G.1, and W is width of the skywell area.

$$tg\ (\theta_1 + \theta_2) = \frac{tg\ \theta_1 + tg\ \theta_2}{1 - tg\ \theta_1 * tg\ \theta_2} \quad \text{eq.1}$$

$$tg\ \theta_1 = H/(L+X)$$

$$tg\ \theta_2 = H/(W-X)$$

$$tg\ (\theta_1 + \theta_2) = \frac{H/(L+X) + H/(W-X)}{1 - H^2/((L+X)*(W-X))} = \frac{-H*(W+L)}{X^2 - (W-L)*X + H^2 - W*L}$$

$$= \frac{H*(W+L)}{W*L + (W-L)^2/4 - H^2 - (X-(W-L)/2)^2} \quad \text{eq.3}$$

For illumination to be maximal, θ should be maximal. For θ to be maximal, $(\theta_1 + \theta_2)$ must be minimal. For given values of H, W and L, in order for $(\theta_1+\theta_2)$ to be minimal, $(X-(W-L)/2)^2$ must be minimal.

$(X-(W-L)/2)^2 \geq 0$; therefore when $X = (W-L)/2$, $(X-(W-L)/2)$ will have a minimum value which is 0, it follows that $(\theta_1+\theta_2)$ will be minimal and θ will be maximal. Thus, when the skywell is centrally located above the utility area, θ is maximal, and illumination is consequently maximal.

Proposition 3 When a high side opening is present in a room co-illuminated by a skywell, the point of maximal illumination will be close to the window.

In figure G.3 below, H_s represents the vertical distance between the plane of measurement of illuminance and the lower edge of the window aperture, while H_w represents the distance between the upper and lower edges of the aperture. P is a point on the plane of measurement of illuminance.

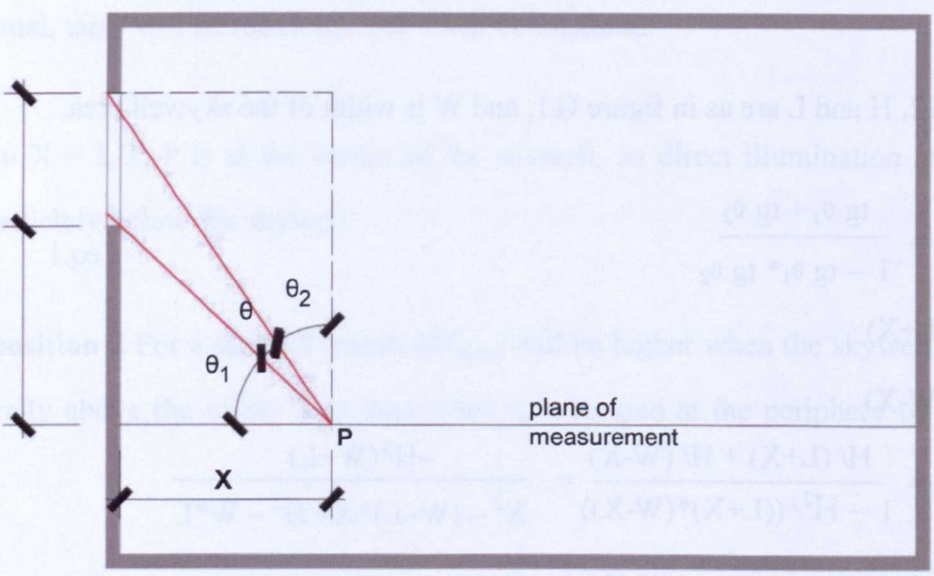


Figure G. 3 Sectional view of a simplified room showing the angle of visible sky θ at a point on the plane of measurement

For illumination at P to be maximal, θ should be maximal and therefore $(\theta_1+\theta_2)$ should be minimal.

$$\mathrm{tg}\,(\theta_1 + \theta_2) = \frac{\mathrm{tg}\,\theta_1 + \mathrm{tg}\,\theta_2}{1 - \mathrm{tg}\,\theta_1 * \mathrm{tg}\,\theta_2} \qquad \text{eq.1}$$

$\mathrm{tg}\,\theta_1 = H_s/X$ (to simply the equations, the thickness of the wall is not considered)

$\mathrm{tg}\,\theta_2 = X/(H_w + H_s)$

$$\mathrm{tg}\,(\theta_1 + \theta_2) = \frac{H_s/X + X/(H_w + H_s)}{1 - H_s/(H_s + H_w)} \qquad \text{eq.4}$$

For given values of H_w and H_s, in order for $(\theta_1 + \theta_2)$ to be minimal, $H_s/X + X/(H_w + H_s)$ must be minimal. $H_s/X + X/(H_w + H_s) \geq 2*\sqrt{H_s/(H_w + H_s)}$, therefore when $X = \sqrt{H_s*(H_w + H_s)}$, the above term from equation 4 will be minimal, so θ will be maximal. Thus when $X = \sqrt{H_s*(H_w + H_s)}$, illumination from the side window will be maximal.

When a central skywell is present, illumination from the side window and from the skywell will combine to produce an illumination maximum towards the window.

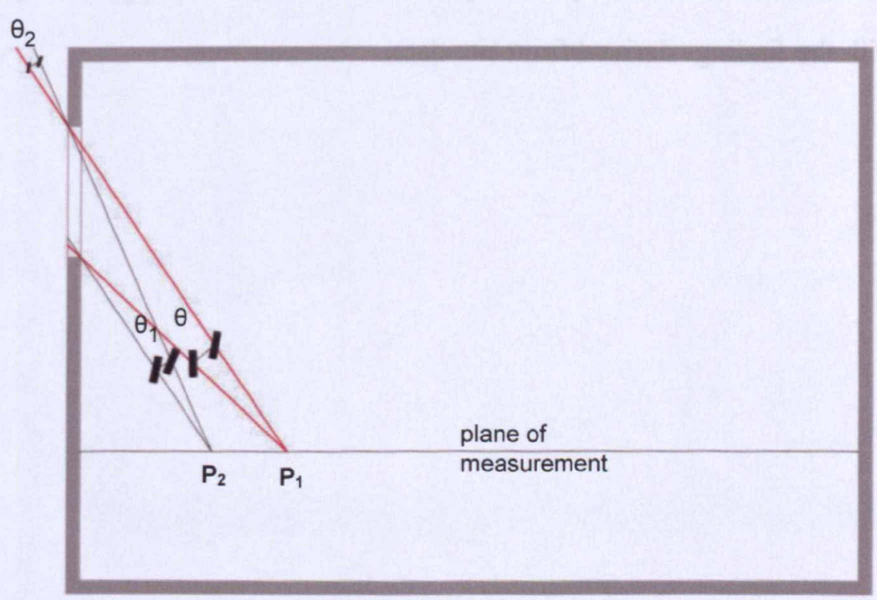


Figure G. 4 Sectional view of a simplified room showing the angle of visible sky θ at two points on the plane of measurement of illuminance

The preceding discussion does not take into account the greater intensity of illumination from the zenith than from shallower angles. In figure G.4, P_2 receives light from a narrower sky angle than P_1, but might be more strongly illuminated because it receives light from region of the sky closer to the zenith. However, it can be concluded that the position of maximal illumination must be between the wall and the distance of $\sqrt{H_s * (H_w + H_s)}$.

In considering proposition 1 and 2, a single vertical plane is examined. In actuality the illumination received at a single point arrives from all around the skywell. None the less, it is legitimate to consider a single vertical plane rather than a solid angle, since the mathematical description is valid for all vertical planes. In the exploration of proposition 3, consideration of a single axial vertical plane is sufficient to derive on expression for the distance between the point of maximal illumination and the wall in which the window is set. The validity of Propositions 1, 2 and 3 is supported by their congruence with the findings derived from site data.

APPENDIX H

Positions of data loggers in the eight Chinese vernacular dwellings

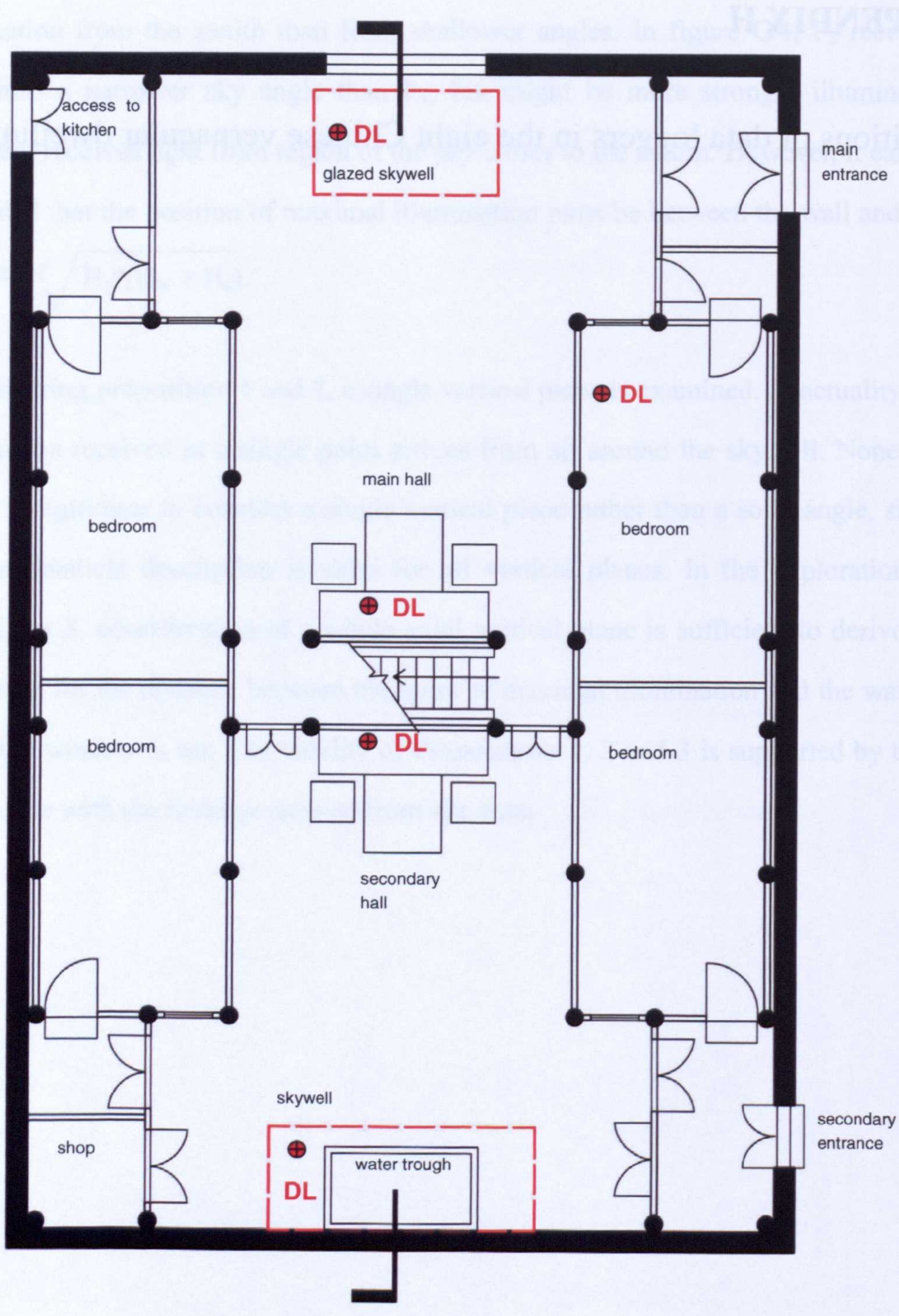


Figure H. 1 Positions of data loggers in Lufu dwelling (Xidi village)

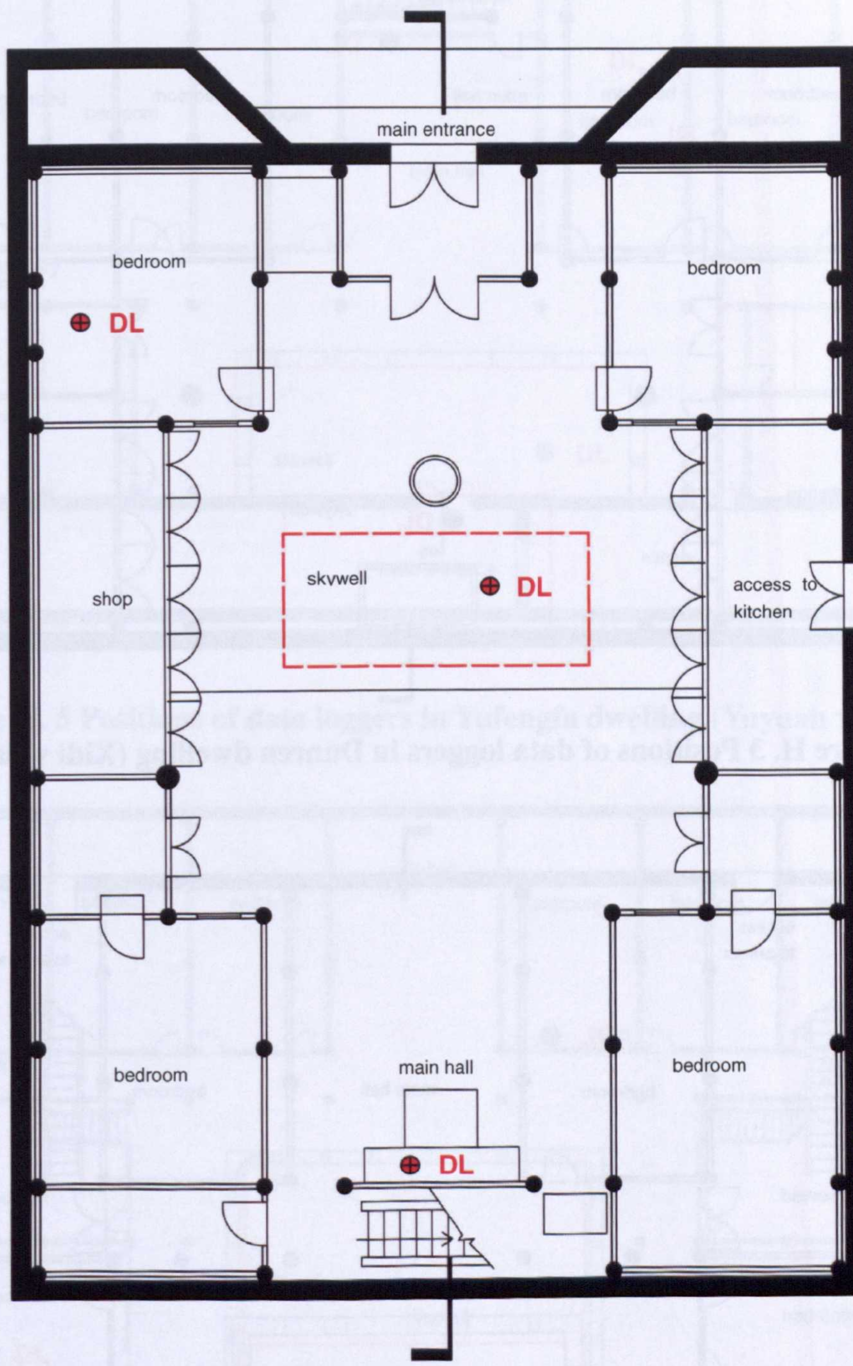


Figure H. 2 Positions of data loggers in Yingfu dwelling (Xidi village)

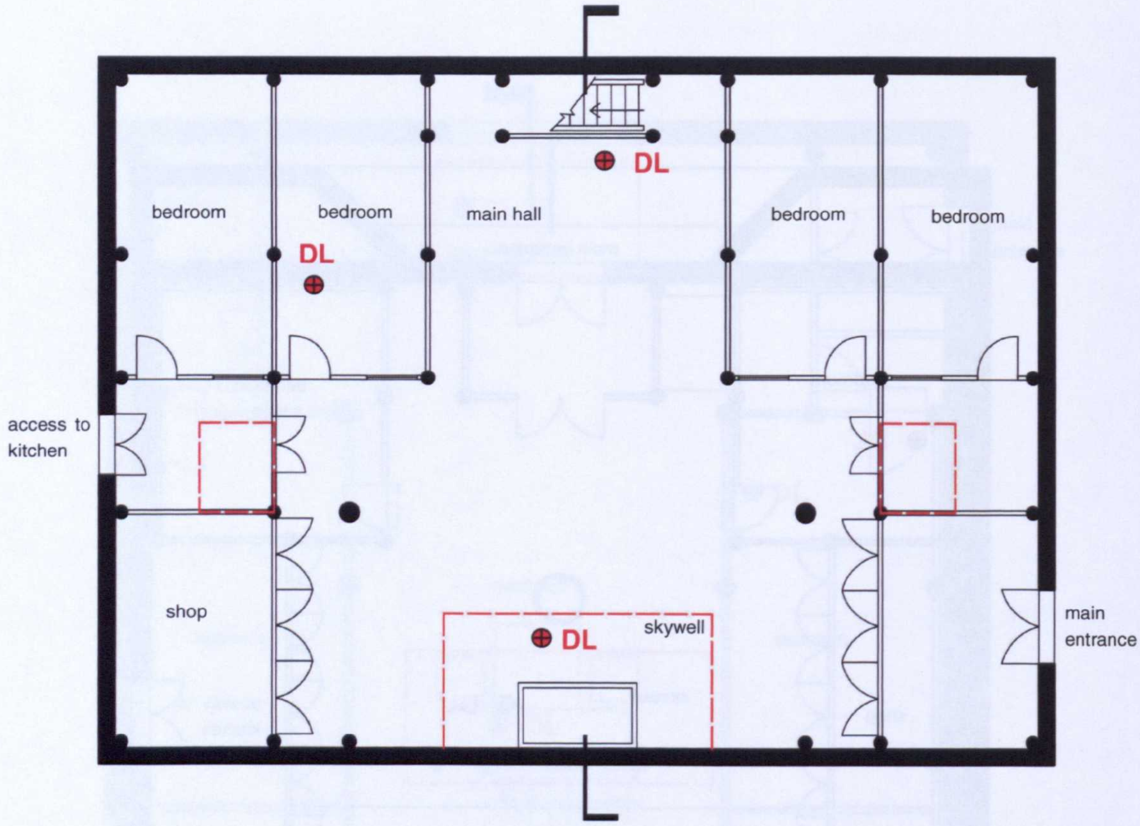


Figure H. 3 Positions of data loggers in Dunren dwelling (Xidi village)

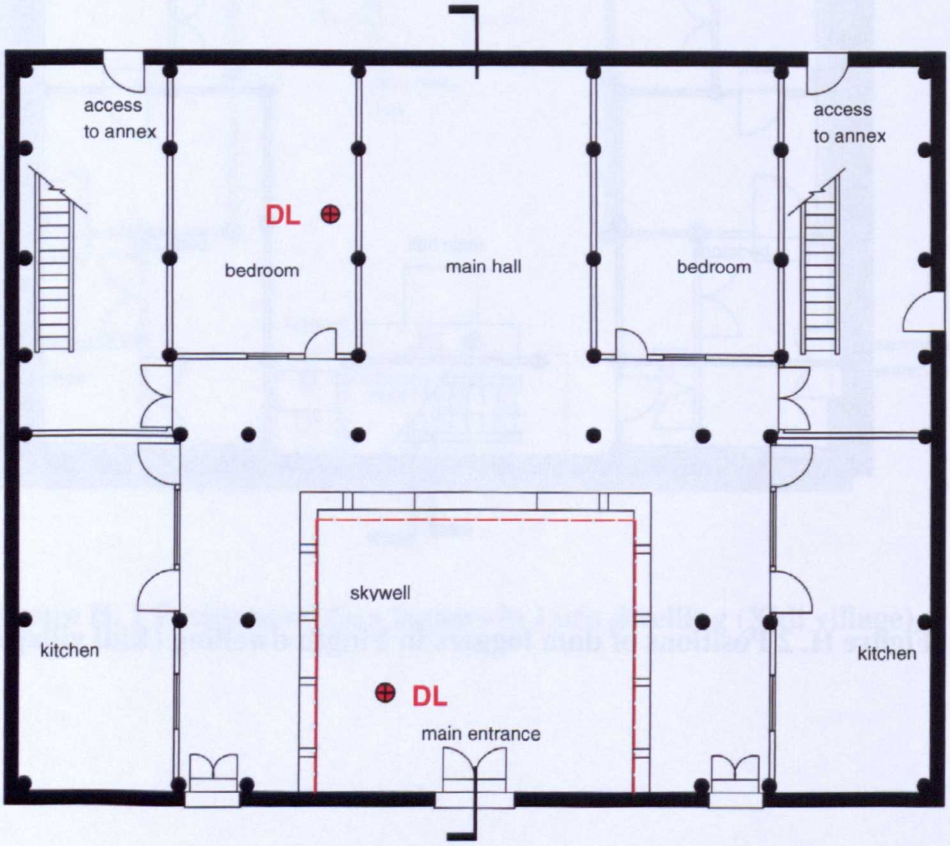


Figure H. 4 Positions of data loggers in Shuting dwelling (Yuyuan village)

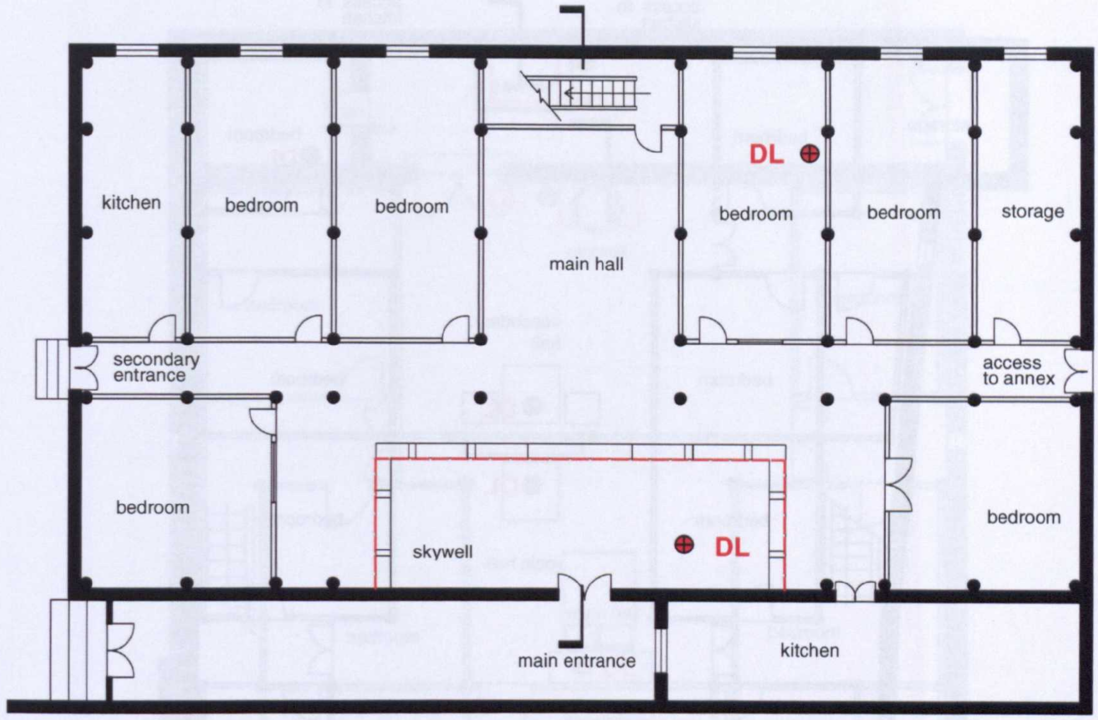


Figure H. 5 Positions of data loggers in Yufengfa dwelling (Yuyuan village)

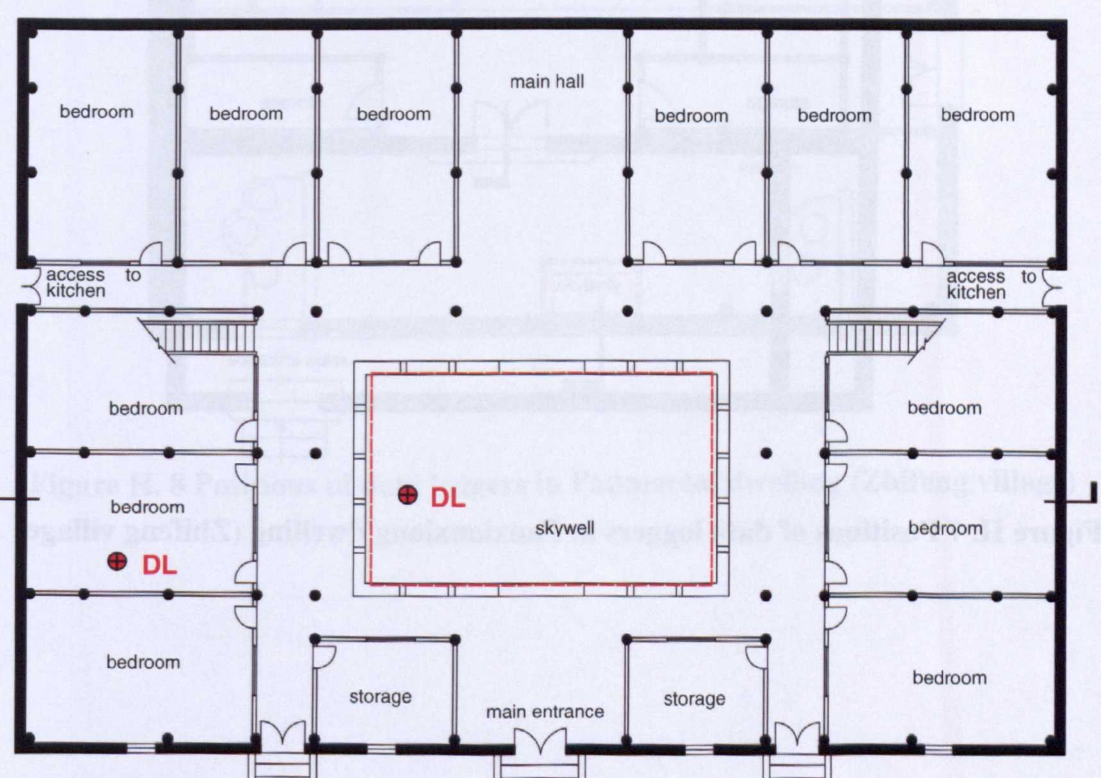


Figure H. 6 Positions of data loggers in Gaozuo dwelling (Yuyuan village)

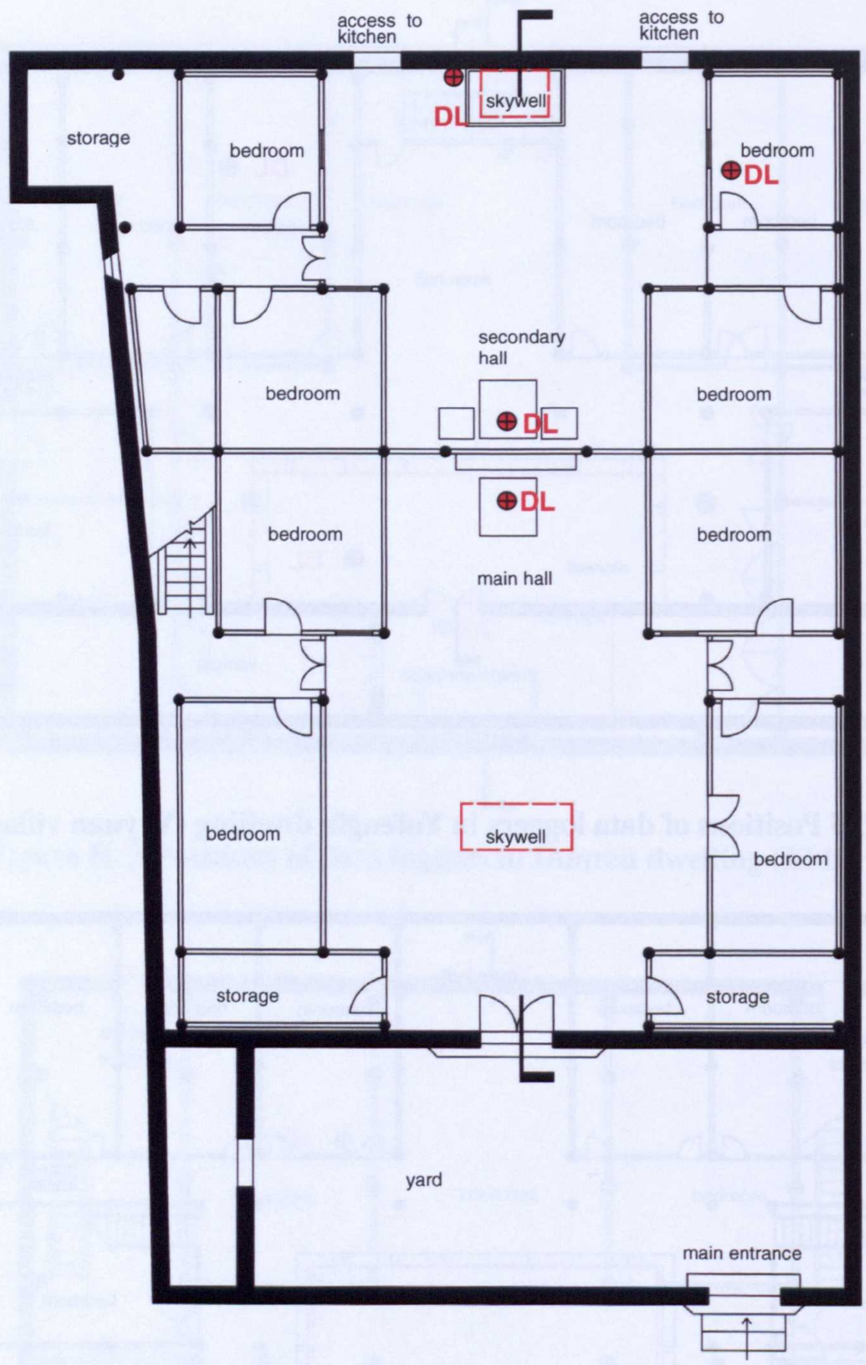


Figure H. 7 Positions of data loggers in Panxianxiong dwelling (Zhifeng village)

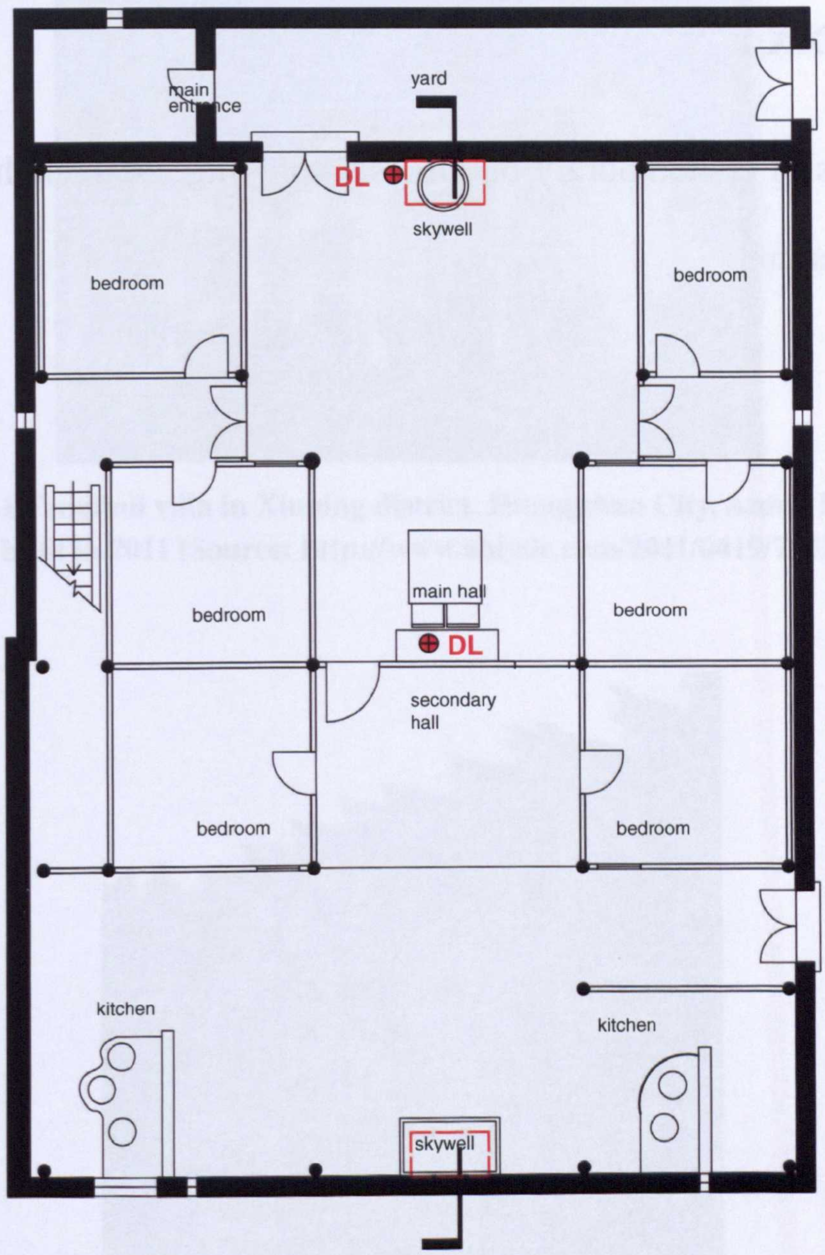


Figure H. 8 Positions of data loggers in Panmaotai dwelling (Zhifeng village)

APPENDIX I

Examples of contemporary buildings employing the horse-head wall design feature

Figure I. 1 Fenglinli villa in Xiuning district, Huangshan City, Anhui Province, China, built in 2011 (Source: http://www.ahlydc.com/2011/0419/7542.html)

Figure I. 2 Fuguimen villa in Xiamen City, Fujian Province, China, built in 2008 (Source: http://www.ffw.com.cn/1/84/97/17194.html)