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Climate responsive building design strategies of vernacular architecture in Nepal

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ABSTRACT

Vernacular architecture is the result of hundreds of years of optimization to provide a comfortable shelter in a local climate using available materials and known construction technologies. Due to the absence of mechanical means, traditional buildings use solar passive measures to achieve thermal comfort conditions. In most developing countries it can be observed that with the modernization of the building sector this traditional knowledge of smart and climate responsive design is being lost. Instead the modern building design is dominated by universal architecture that neglects local climate conditions and traditional construction techniques and materials. This paper reviews examples of vernacular architecture and its building elements in Nepal and analyses in a qualitative manner which bioclimatic design strategies were applied.

1. Introduction

Worldwide around 40% of energy is consumed in buildings [1]. Due to population growth, increased urbanization and improvements of living standards most of energy consuming buildings will be located in the urban centers of the developing world. The depletion of energy resources and the risk of climate change are demanding for a sustainable development path based on renewable energies and energy efficiency [2]. Climate responsive or solar passive building design can play a significant role in reducing the energy demand of buildings without compromising modern living standards.

The most important function of buildings is to provide shelter with appropriate thermal and visual indoor comfort for its occupants. The comfort level in a building depends upon the designs in combination with the outdoor climate. Design irrespective to climatic conditions means either to create uncomfortable indoor environments or to increase the need for maintaining thermal comfort through artificial means. As our ancestors had fewer technologies available for heating and cooling, vernacular houses are mainly designed to optimize the use of natural resources like the sun and wind [3–7]. Several studies have proven that better thermal performance can be achieved by passive measures in vernacular architecture [6–9]. The developing world's construction practices until recently were basically grounded onto this knowledge of traditional building techniques. However, modernization together with the need of effective and fast provision of shelters for the increasing population has flooded the market with new building designs, technologies and materials. These are rapidly accepted by users who demand for such designs and express increased thermal comfort expectations. The group of new building professionals does often apply new designs without considering local climate conditions.

Consequently, traditional houses are disappearing and the knowledge about its construction practices is slowly forgotten. Therefore, the need to document this knowledge of traditional constructions practices is evident. Few studies [10–12] have analyzed vernacular architecture from specific locations of Nepal in regard to climate responsiveness. This research is the first comprehensive study on solar passive design features of a large number of vernacular houses from all over the country. Following the principle "Learning from the past" [13], it might be the groundwork to develop new and more sustainable design strategies for the fast growing building sector that consider the local climatic conditions while aiming at the reduction of energy-intensive and expensive artificial means to provide comfort.

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2. Methodology and structure

Besides the climatic variations in Nepal, diversity of culture has led to a large range of different architectural expressions that are mostly documented by anthropologists, ethnologists and architects [14–21]. This research is based on a literature review and field research in Nepal.

In a first step, the paper gives an overview of the research country Nepal focusing on aspects that are most relevant for the development of vernacular architecture such as cultural and geographical diversity, local materials and climate.

Secondly, the climate conditions in Nepal are investigated, based on climate data from four weather stations that are representing the most important climatic zones of the country. The study identifies the dominating bioclimatic design strategies for the four predominating climates using three tools: Olgyay's bioclimatic chart [3], Givoni's psychrometric chart [4] and Mahoney Table [5]. Olgyay's bioclimatic chart is based on the outdoor climate factors considering humidity versus temperature [3]. Monthly data of minimum and maximum relative humidity and temperature are plotted onto the chart for each month. If the plotted line falls within the comfort zone, conditions are comfortable in the shade and in still air. If the line falls partly or totally outside of the comfort zone, corrective measures are necessary such as the use of solar radiation, air movement or evaporative cooling [3]. Givoni uses the psychrometric chart for the bioclimatic analysis [4]. A psychrometric chart is a graph of the thermodynamic parameters of moist air at a constant pressure. Givoni's chart predicts the comfort conditions within the building based on outside climate factor. As in Olgyay's chart the combination of monthly temperature and relative humidity indicates the recommended passive design strategy for each month. The chart contains the comfort zone, marked by a solid line and several zones for passive design strategies, namely passive solar heating, humidification, evaporative cooling, natural ventilation, and high thermal mass [4]. The Mahoney Table methodology is a set of reference tables that use monthly climate data of temperature, relative humidity and precipitation to calculate indicators for heat and cold stress as well as humid and arid conditions for each month. The combination of these indicators results into simple design recommendation, e.g. "reduce sun exposure", "compact building layout' or "medium sized openings" [5].

In the third step, this research analyses a variety of vernacular houses in Nepal, located in different climatic zones, in respect to their design and construction in order to determine the applied climate-responsive design strategies. For the analysis of traditional housing the approach of [22,23] was adapted. Both studies use a set of building features to analyze the design and construction techniques of the vernacular buildings in regard to climate-responsiveness. This research has selected the following features to assess the vernacular houses of Nepal in a qualitative manner: settlement pattern, building form and orientation, building stories and internal space arrangement, design and construction materials of walls, roof, foundation, floors, ceilings and openings.

Concluding, the study compares the design strategies identified in the second step based on bioclimatic approach with the actually applied strategies in the vernacular houses aiming to prove the hypothesis that traditional houses are very much adapted to the local climate conditions.

3. Research region

3.1. Geographical diversity

Nepal's territory expands about 800 km east–west and 200 km north–south and displays a highly varying topography (Fig. 1).

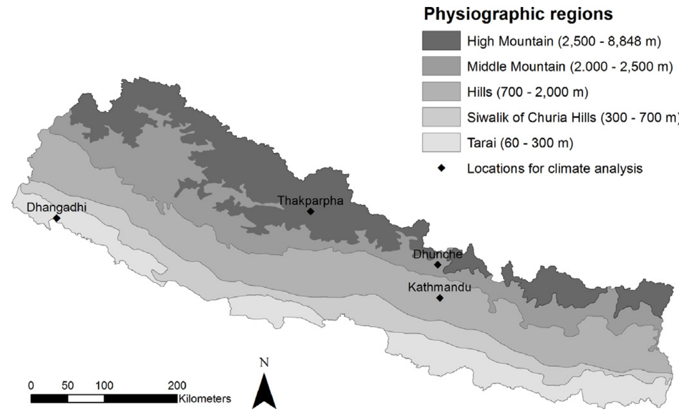

Fig. 1. Physiographic regions of Nepal
Adapted from [38].

Altitude reaches from 65 m.a.s.l. (meters above sea level) to 8848 m.a.s.l. at the Mount Everest, the highest summit of the world. This is leading to a variety of climatic and vegetation zones. Climate has also strongly influenced the traditional architectures. Furthermore, Nepal's population is composed of a large number of different ethnic groups as a result of successive migration of Tibeto-Burman people from the north-east and Indo-Aryans from the south-west [24]. Each ethnic group has its own culture, religious beliefs as well as traditions, and in most cases, also language. Geographical diversity has resulted in diverse socio-economic and cultural patterns and, thus, in a variety of different architectural expressions. Typical houses of a number of ethnic groups (Tharu, Limbu, Newar, Sherpa, Tamang, Thakali, etc.) are analyzed within this study.

3.2. Traditional building materials

The local availability of certain building materials, in particular mineral based materials, depends on the geology of the location. Due to the geodynamic process in the Himalayan region Nepal's geology has a high complexity of many thrusting, faulting, folding and metamorphic effects. Nepal is divided into five distinct morpho-geotectonic zones from south to north: the Tarai Tectonic Zone, the Churia Zone (also called: Siwalik), the Lesser Himalayan Zone, the Higher Himalayan Zone and the Tibetan Tethyan Zone [25]. These five zones compromise a total number of eight geomorphic units which lead to different kind of available materials for building construction (Table 1). On the other hand climatic conditions determine the typical vegetation in a region and, thus, the availability of organic building materials like wood.

The Tarai Region's geology is mainly characterized by coarse, gravel, and finer sediments. Rich fertile alluvial soil is the basis for fertile agricultural land and dense Sal forest. Therefore, traditionally abundant reserves of wood, thatch, and further biogenic material as well as mud and sand are locally available for house construction.

In the Hilly Region of Nepal more stones (schist, phyllite, gneiss, granite, limestone and slate) are available and used as construction material. In larger valleys like Kathmandu lacustrine soil deposits are used for brick making. Sand and gravel is available from the riverbeds. Dense vegetation in the form of Sal or hill forests lead to the wide availability of timber. Fertile land and favorable climate conditions allow for the production of other vegetation based building materials like thatch.

The Himalayan Mountain Region provides abundant resources of stones, rocks and mud. Due to the small availability of fertile land

Table 1
Availability of traditional building materials.

Region	Geomorphic unit	Width (km)	Altitudes (m)	Main rock type	Soil type	Typical vegetation	Available traditional building materials
Tarai Region	Northern edge of Gangetic Plain	20–50	60–200	Alluvium: coarse, gravel in the north becoming finer southwards	Rich fertile alluvial soil, gravelly and sandy soil	Fertile agricultural land, dense Sal forest	Abundant: wood, thatch, daub, other biogenic materials, mud, sand, gravel Scarce: stones, rocks
Hilly Region	Churia Hills or Siwalik	10–50	200–1000	Sandstone, mudstone, shale, conglomerate	Gravelly and sandy soil	Sal forest	Abundant: stones, slate, timber, thatch, clay for brick making, sand, gravel
	Dun Valleys	5–30	200–300	Alluvium: coarse to fine sediments	Rich fertile alluvial soil	Sal forest	
	Mahabharat Range	10–35	1000–2500	Schist, phyllite, gneiss, quartzite, granite, limestone, slate	Fertile residual soil	Along middle slope: hill forest,	
	Middle Mountain	40–60	200–2000	Schist, phyllite, gneiss, quartzite, granite, limestone, in valleys: also finer alluvial sediments	Fertile residual soil, in valleys: Lacustrine soil (fertile and clay for brick making)	Mixed evergreen forest, open grazing and woodlands	
Himalayan Region (Mountain)	Fore Himalaya	20–70	2000–5000	Gneisses, schists and marbles	Low fertile glacial soil	Evergreen coniferous forest up to 4000 m, alpine grassland up to 4500 m	Abundant: stones, rocks, mud Scarce: timber and other biogenic materials
	Higher Himalaya	10–60	>5000	Gneisses, schists and marbles	Low fertile glacial soil	No vegetation	
	Inner and Trans Himalayan Valleys	5–50	2500–4000	Gneisses, schists and marbles; in Trans Himalayan Valley: also finer sediments from limestone, shale, sandstone	Low fertile glacial soil	Scarce vegetation	

Adapted from ([1,16–18]9).

and the harsh climatic condition timber and other organic materials for building purposes are rather scarce.

3.3. Climate analysis

Nepal has large climatic variations from hot sub-tropical climate to cold tundra climate. Several geographical factors influence the climate of the country, like latitude, altitude, slope orientation, prevailing as well local winds, and vegetation [24]. Two climate classifications are presented in the following. However, this study uses the more detailed country specific classification from Shrestha [24].

According to the global Koeppen-Geiger Climate classification [26] Nepal has four climate zones: warm climate with dry winters and hot summers (Cwa), warm climate with dry winters and warm summers (Cwb), snow climate with dry and cold winter and cool summer (Dwc) and tundra climate (ET).

Shrestha [24] divides Nepal into five climatic regions, namely, sub-tropical, warm temperate, cool temperate, alpine and tundra climate (Table 2). Nepal's climate has two main seasons: winter that lasts roughly from October to March and summer from April to September. Due to the fact that Nepal's climate is strongly influenced by the Monsoon the summer season can be subdivided into a hot and dry period (from April till mid-June) and a warm and rainy period (from mid-June till September) [24]. To evaluate the bioclimatic or climate-responsive building design strategies for Nepal, local climate data from four typical locations of Nepal were collected and analyzed. Tundra climate is not considered in the analysis due to the fact that there are very few settlements above 5000 m.a.s.l. Fig. 2 illustrated the climate conditions of four location (see Fig. 1), namely Dhanghadi, Kathmandu, Dhunche, and Thakmarpha based on monthly data series of 36, 35, 22, and 34 years, respectively.

Dhanghadi (28°48′ N, 80°33′ E) is situated in the Far western Tarai of Nepal has sub-tropical climate dominated by the monsoon (Koeppen: Cwa). During winter months the mean temperature is about 15 °C. Summers in Dhanghadi are very hot exceeding temperatures well above 30 °C. During winter and the dry summer season the monthly average precipitation is between 4 mm and 72 mm. When monsoon starts in June the rainfall increases up to 550 mm per month.

Kathmandu (27°42′ N, 85°22′ E) is representing the warm temperate climate of Nepal that is mainly dominant in the Hilly Region (Koeppen: Cwb). During summer outdoor conditions are comfortable with average temperatures between 20 and 24 °C. In winter the mean temperature drops down to 10 °C. In January minimum temperatures of 2 °C can be reached during night time. The dry season has monthly precipitation between 9 mm and 106 mm while during rainy season 365 mm are expected in average.

Dhunche (28°48′ N, 85°18′ E) situated in the Himalayan Mountains of Nepal at an elevation of almost 2000 m is selected to represent the cool temperate climate (Koeppen: Dwc). Summers are significantly cooler than in Kathmandu while average temperature during winters are only little colder. However, Dhunche is considerably more humid with an annual rainfall of almost 2000 mm. The lowest precipitation occurs in November and December. Most rain falls in July and August.

Thakmarpha (28°45′ N, 83°42′ E) is located in the rain shadow of Annapurna range having a dry and cold alpine climate (Koeppen: Dwc). In contrast to the three other selected locations Thakmarpha has a very low annual precipitation. During winter, temperature drops below 0 °C. In summer season the mean maximum temperatures rises up to 21 °C. Monthly monsoon precipitation is only about one tenth (44–67 mm) compared to the sub-tropical Tarai.

Table 2
Nepal's climatic zone (after [24]).

Climatic zone	Altitude	Mean temperature		Annual average precipitation	Selected locations
		Winter	Summer		
Sub-tropical	0–1200 m	15 °C	>30 °C	100–200 mm	Dhanghadi
Warm temperate	1200–2100 m	10 °C	24–30 °C	100–200 mm	Kathmandu
Cool temperate	2100–3300 m	<5 °C	20 °C	150 mm	Dhunche
Alpine	3300–5000 m	<0 °C	10–15 °C	25–50 mm in snow	Thakmarpha
Tundra	Above 5000 m	Below 0 °C		Snowfall	

4. Climate-responsive design strategies for Nepal

For the four representative locations the following design recommendations were identified by using Olgyay's bioclimatic chart [3], Givoni's psychrometric chart [4] and Mahoney Table [5] as described in the methodology above. Exemplarily, Givoni charts for four climates are shown in Fig. 3.

4.1. Sub-tropical climate

The enhancement of air movement is essential for the subtropical climate of Nepal. It is recommended to allocate rooms single-banked and provide permanent provision for air movement, e.g. through cross or stack ventilation. According to the Mahoney Table (Table 3) houses should be oriented north and south (long axis east–west) to reduce solar heat gains, particularly during the hot season. Openings should be of medium size (20–40% of outer wall area) and exclude direct sunlight during summer months through shading devices. High thermal mass with night ventilation might provide thermal comfort, particularly during the hot and dry summer period. However, light building materials are recommended for the hot and humid monsoon season. Light, well insulated roofs are recommendable for this climate. Olgyay's chart and Givoni's chart indicates that solar radiation in form of solar passive heating can be sufficient to provide thermal comfort during the short winter period. The protection of the building from heavy monsoon rain is necessary according to the Mahoney Table (Table 3).

4.2. Warm temperate climate

Temperature in Nepal's warm temperate climate does not drop down drastically during winter. Therefore, solar radiation combined with thermal mass of the building can keep the indoor temperature at a comfortable level. Buildings should be oriented with the longer façade toward south and have medium sized openings; by this way solar penetration of the south façade could provide solar heat gains in winter (when the sun angle is low) and reduce overheating in summer. Shading devices for windows are needed for the summer period. From December to January active solar or conventional heating might be partly needed. The Mahoney Table recommends heavy external and internal walls and light but well insulated roofs. However, according to Givoni's chart thermal mass is only favorable during April and May to balance the internal temperature swing (Fig. 3). In humid summer months air movement is the essential bioclimatic design strategy for Nepal's warm temperate climate. Therefore, single-banked room arrangement or other means of natural ventilation are recommended (Table 3). Heavy rains during monsoon season claim for protection and adequate rainwater drainage.

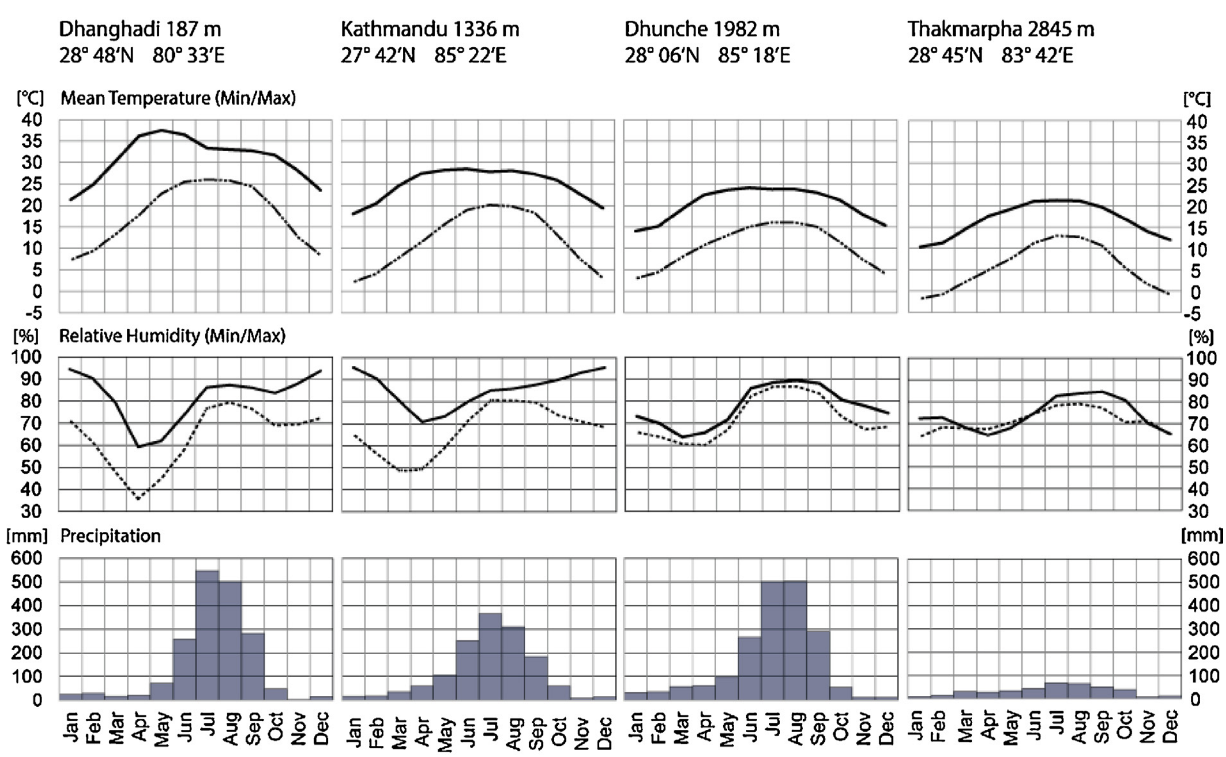

Fig. 2. Climate diagrams of four selected locations in Nepal (after [39]).

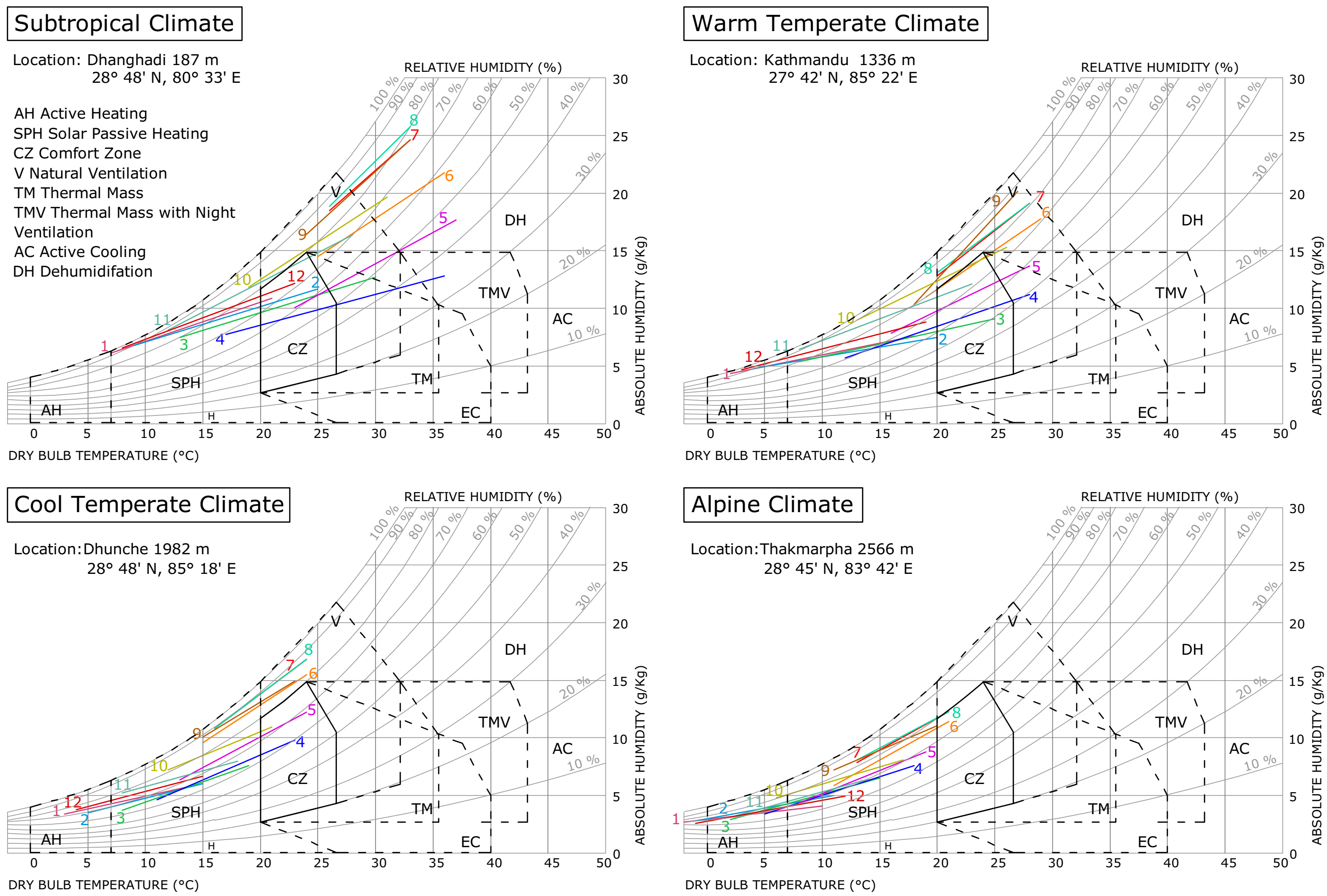

Fig. 3. Givoni's bioclimatic chart for four representative climate zones of Nepal.

4.3. Cool temperate climate

In cool temperate climate the use of solar radiation for passive heating is an effective design strategy during the longer winter period from October to March. In contrast to warm temperate climate a compact building layout is recommended by the Mahoney Table. During half of the year active solar or conventional heating is needed, particularly during night time. However, due to high solar radiation in winter solar passive heating combined with thermal mass (heavy walls and floors with thermal time-lag of more than 8 h) can reduce the need for conventional heating considerably. The rest of the year passive solar heating solely can provide comfort during cool nights. From June to September natural ventilation of the building is needed to avoid over-heating during the day (Table 3). According to Mahoney Table openings should be medium sized and protection from heavy rains as well as adequate rainwater drainage is necessary.

4.4. Alpine climate

In contrast to the conditions within the cool temperate climate zone, Nepal's alpine climate is far colder and dryer. Protection from the cold is necessary from October to April (Table 3). Therefore, compact building layout and small openings (15–25% of outer wall area) are recommended. According to the Mahoney Table room arrangement should be double-banked with temporary provision for air movement during summer days. Heavy external and internal walls are dominant climate-responsive design strategies to enhance solar passive heating effect for large temperature swing between day and night. In contrast to Nepal's temperate climates heavy roofs with thermal lag of more than eight hours are desired. Active solar or artificial heating is required during long winter periods. In summer nights comfort can be achieved if the building's thermal mass can store enough heat that is gained from solar radiation during the day. Low precipitation amounts

Table 3
Recommended design strategies for each month in different climate zones of Nepal according to Mahoney Table.

Design strategy	Subtropical climate												Warm temperate climate												Cool temperate climate												Alpine climate											
	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D
H1: Air movement essential							■	■	■	■								■	■	■	■	■								■																		
H2: Air movement desirable		■												■	■	■	■	■	■	■	■	■	■							■	■	■	■	■								■	■	■	■			
H3: Rain protection necessary						■	■	■	■									■	■	■										■	■	■	■															
A1: Thermal capacity			■	■	■	■									■	■	■								■	■	■	■	■								■	■	■								■	■
A2: Outdoor sleeping				■																																												
A3: Protection from cold	■												■											■	■	■	■								■	■	■	■	■	■						■	■	■

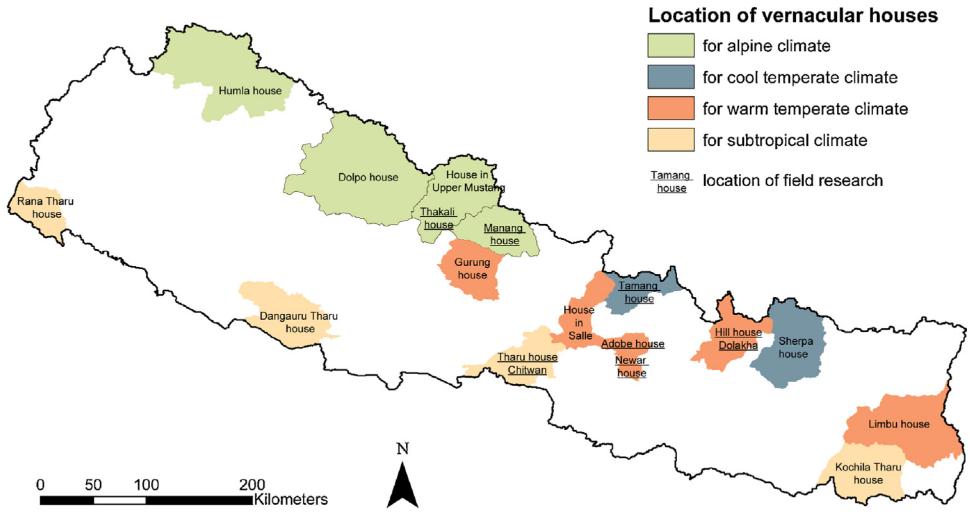

Fig. 4. Nepal map with location of analyzed vernacular houses.

eliminate the need to protect the building from heavy rains or high humidity.

5. Climate-responsive design in vernacular houses of different climate regions

A total number of 19 vernacular house are analyzed in the following according to the climate classification. The locations of the houses are shown on the map in Fig. 4.

5.1. Sub-tropical climate

The analysis of vernacular architecture in Nepal's subtropical climate refers to the following houses: Tharu houses in Chitwan (field research), Traditional Tarai houses [12,27], Rana Tharu house in Kanchanpur district of Far-western region [15], Dangaura Tharu house in Dang district of Mid-western Region [15,16] and Eastern Kochila Tharu in Morang and Sunsari of Eastern Nepal [15].

Due to the dominating tropical monsoon climate houses have to protect from heat and heavy rainfall [27]. Local materials mainly used are cane, timber and thatch [12]. They lead to the design of a comfortable 'breathing' house that means the building envelope is rather permeable and enhance natural ventilation [15].

5.1.1. Settlement pattern

The traditional settlement pattern in sub-tropical climate of Nepal is rather loose than dense. Tharu houses are either loosely situated along the road or they create clusters of semi-closed compounds [15,16]. Rana Tharu houses are arranged around a courtyard that is open to at least one side so that breezy winds can flow through the settlement. In the Dangaura Tharu village the long houses are arranged in one single row along the road with a wide open yard in front of each house [12]. This facilitates easy penetration of air through the houses.

5.1.2. Building form and orientation

The buildings have rectangular floor plans that are enclosed with low walls, sometimes no higher than 75 cm [12]. Dangaura and Eastern Kochila Tharu houses are found to be typical Longhouses while Rana Tharu houses have a more compact floor plan. The longer axis of Dangaura Tharu houses is more than twice of the shorter axis. The longer facade is typically oriented north–south which reduces the exposure to the sun.

5.1.3. Building stories and internal space arrangement

Most vernacular houses in Tarai have only one single floor or, like Rana Tharu houses, a ground floor with a mezzanine that is used as storage [15]. They have high ceilings for enhancing permanent ventilation that is strongly needed in this hot and humid climate. However, due to increasing urbanization and higher settlement density one of the Tharu studied houses in the Eastern Nepal was found to be of two-story.

The spaces in the studied houses are organized more in a horizontal manner. The internal space is almost undivided and, thus, enhances a continuous natural circulation of cool air coming from the shaded area below the eaves [12]. The studied Longhouses have only one division that does not reach the roof so that air can freely circulate (Fig. 5). In Rana Tharu houses big vessels, which store grain, are used for dividing the space. In all Tharu houses semi-open spaces in form of a veranda are occupying a large part of the floor plan. The verandas are shaded by the roof overhang and provide an additional comfortable space for daily activities (Fig. 6). Having two story houses, the Eastern Kochila Tharus use the second floor mainly as sleeping rooms and storage. One-third of the second floor plan consists of a veranda that provides a breezy semi-open sleeping space for hot and humid summer months [15].

5.1.4. Walls

The walls of traditional Tarai houses are rather light and mostly made of wattle and daub [27]. The upper portion of the exterior wall is observed to be of bamboo strips that are loosely woven into an open mesh which provide day lighting and permanent ventilation. Unplastered walls of wood or reed have random gaps. External walls might also be made of thin woven cane mats tied onto a timber frame, rendered with mud plaster and white washed [12].

5.1.5. Roof

Most traditional roofs in Nepal's subtropical climate are made of thatch in the form of a pitched roof [12,15,16]. The triangular opening at either end and the low windows ensures the permanent inflow of air from the shaded area below the eaves that leads to inside temperatures that are usually much lower than outside temperatures [12] (Fig. 7). Dangaura and Kochila Tharu houses have also light, well insulating thatch roofs. The wide roof overhang protects walls from direct sun radiation. Verandas are formed by extending the roofs and provide a comfortable place to work and even sleep at night [27].

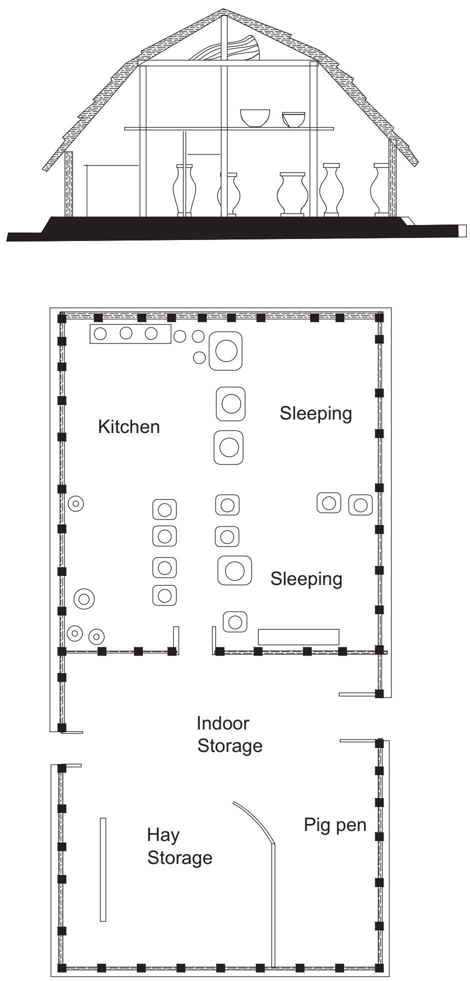

Fig. 5. Floor plan and section of Dangaura Tharu House (after [15]).

5.1.6. Foundation, floor and ceiling

Typically Tharu houses are found on a plinth made of stone or earth to protect the interior from flooding during raining season [12]. Some houses are built on wooden piling from 90 to 300 cm for the same reason [27]. The elevation from the ground by piling as well as high ceilings enhances air circulation within the building. Floors are made of compacted earth, clay tiles or locally available stones that are possibly covered by cement plaster.

Fig. 6. Tharu house with wide roof overhang and shaded veranda in Chitwan.

Fig. 7. Gable opening for air circulation in Tharu House, Chitwan.

5.1.7. Openings

Buildings have very few and low windows that together with an opening in the roof enhance the air circulation to provide comfort during hot and humid summer months [12]. Shading of the windows is provided through roof overhangs and the planting of trees around the buildings [27].

5.1.8. Results

It was observed that settlements are arranged by a loose pattern that allows air penetration – a typical design strategy for hot and humid climates. Rectangular building form and horizontal space arrangement in one story is dominant. Wall and roofing materials are rather light than heavy and are often permeable to air. The high and almost undivided interior space together with the openings in wall and roof enhances the natural ventilation within the building. In some houses openings are located in such a way to foster stack ventilation. Wide roof overhangs including the provision of shaded veranda space reduces the direct solar gain through walls and openings. For comparison characteristics of all analyzed houses in subtropical climate are listed in Table 4.

Concluding, the traditional house design in subtropical climate of Nepal is very climate responsive. Main strategies like enhancing air movement within the building and protecting from the strong solar radiating are considered.

5.2. Warm temperate climate

Representing the traditional architecture in the warm temperate climate of Nepal, house typologies from different ethnic groups and locations in the Hilly Region were studied, including Hill houses in Dolakha district (field research), Houses in Salle in Dhading district [28], Newar houses in Kathmandu valley ([14,20,21], field research), the Indo-Nepalese house in central Nepal [16], an Adobe house in Kathmandu Valley (field research), the Gurung houses in Thak Village of Kaski district [12,29] and the Limbu house in Eastern Nepal [16,30,31].

5.2.1. Settlement pattern

Settlements in Nepal's warm temperate hill climate are rather of scattered and dispersed character. Houses are placed on the hill terraces along the slope surrounded by each family's fields. The villages and towns built by the tribe of Newars only, have a denser settlement pattern with its characteristic courtyards [21].

5.2.2. Building form and orientation

There are several types of building forms strongly depending on settlement density and ethnicity. Newar houses being part of compact settlement with high density are arranged to create interconnected courtyards [14,20]. The courtyards are designed in such a way to allow solar penetration of buildings and provide a warmer outside space for all kind of household activities during sunny winter days. In contrast to Newar settlements, other traditional houses in hilly Nepal are rather dispersed [16]. Most of the houses have a rectangular shape except Gurung houses that have a round floor plan [12]. Often the elongated plan is situated on the sunny slope of the hills with the longer facade facing toward the south, south-east or south-west (Fig. 11). Larger windows are placed in the longer facade, i.e. facing the sun. Around the open courtyard, which is situated in front of the main building, one or two annex buildings for cattle or storage can be placed. The studied Limbu house was found to have a more compact floor plan. And in contrast to other dispersed houses the shorter facade is faced southwards. Due to religious beliefs Limbu houses are always located parallel to a river bed [30].

5.2.3. Building stories and internal space arrangement

It was observed that traditional houses in non-Newar settlements have not more than two stories. Gurung and Limbu houses have only one and a half stories; the ground floor is the main living area [12,29]. Newar houses have typically three or three and a half stories [11,20,21]. Until the early 16th century residential houses were not allowed to exceed height of the temples in Newar settlements [20]. The low room height being between 1.6 and 1.9 m makes it easier to heat the building during winter season.

Depending on the number of stories, building space is arranged either horizontally or vertically. Having only one a half floor, the space in Limbu and Gurung houses is organized more horizontally. The interior of the Gurung house is an almost open space with only few divisions having a fodder under the roof [29].

In Indo-Nepalese houses the ground floor is also a big open space designated for activities like cooking, dining, meeting and worshipping which are sometimes visually divided by lower walls [16]. The first floor is primarily used as granary and storage for family's valuables and, possibly, as bedroom if the space in ground floor is not sufficient for all family members.

Similarly, in Hill Houses of Dolakha the kitchen and main living area are located on the ground floor while sleeping and storage functions are on the first floor. The space under the roof creates another half story and is used as storage; it is ventilated through small windows at each gable end. The access to the second floor is either provided by a wooden leader inside the building or outside, if the house has a balcony (Fig. 11). A very important part of the house is the veranda which is a semi-open space in front of longer facade normally covered by the roof or the balcony. Verandas and balconies often have closed sides to provide protection from cold wind.

Spaces in Newar houses are vertically planned (Fig. 8). The ground floor is only used for entering the house or sometimes as storage and creates a buffer to the cold and humid ground. The bedrooms are located in the first floor while the main living area is in the second floor. Both receive enough solar radiation through the windows to heat up the room during the day. The space under the roof (attic space) is used as kitchen with an open fireplace [11]. Due to the location of the kitchen on the top of the building, living and bed rooms are protected from overheating in summer. Rooms are found to be double-banked [11]. The courtyard of the Newar houses is an important semi-open space for work. It is designed in such a way to be sunny in winter and shaded in summer.

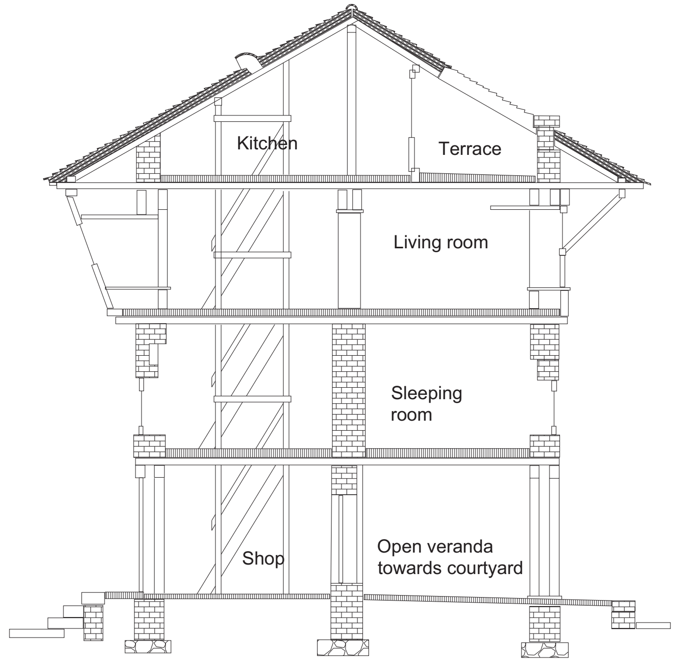

Fig. 8. Section of Newar house with vertical space arrangement (after [21]).

5.2.4. Walls

The walls of houses in Hilly Nepal are mostly made of locally available stones in structural bearing random rubble masonry. Clay and earth are used as mortar. The exterior walls can be up to half meter thick which leads to a high thermal mass of the building. Walls are mostly plastered inside and outside using white, ocher or red mud. The final plaster inside is a thin layer of fin red mud and cow dung is used [16]. Only Gurung houses are made of mud, timber cane and thatch [29]. The walls consist of timber planks and lathe covering both sides with a mixture of mud and cow dung [31]. Newar architecture being the most developed in the region is using sundried or burnt clay-bricks as main walling material (Fig. 9). The walls have a thickness between 28 cm and 70 cm, resulting in a high thermal mass of the building. The outer wall is made of burnt bricks while on the inner side sun-dried inside bricks are used [14,20]. The application of only sundried brick walls (adobe) is also common.

Fig. 9. Hill house in Dolakha with shaded terrace and balcony.

Table 4
Characteristics of vernacular houses in subtropical climate of Nepal.

	Tharu house in Chitwan	Traditional Tarai houses	Rana Tharu house	Dangaura Tharu house	Kochila Tharu house
Settlement pattern	Scattered clusters	Loose clusters of semi-enclosed compounds	Loose pattern around open courtyard	Loose, along the road side	Loose building clusters along road
Building form	Rectangular	Rectangular floor plan	Compact layout	Elongated	Elongated
Building orientation	n.s.	n.s.	Longer façade north–south wards	Longer side east–west oriented	Long facades east–west
Building stories	1	1	1.5	1	2
Internal space arrangement	Horizontal, few divisions	Horizontal manner, almost undivided open space	Horizontal, mezzanine used as storage	Horizontal, few division	Mainly horizontal, 2nd floor includes open veranda
Semi-open spaces	Veranda	Veranda	Open courtyard, veranda	Veranda	Open courtyard, veranda in second floor
Wall material	Wattle and daub, straw and mud, timber, bamboo	Mud plastered woven cane mat tied on timber frame	Mud plastered timber/bamboo walls	Low walls of wood and bamboo covered by mud layer	Lumber on timber structure
Wall thickness	Very thin	Thin, permeable to air	Thin	Thin	Thin, permeable to air
Roof material	Thatch	Thatch or tiles	Tiles	Bamboo lathes with thatch covering	Thatch
Roof type	Pitched roof	Hipped roofs	Pitched roof	Hipped roof	Pitched roof
Roof overhang	Wide	Wide	Wide	Large	Large
Foundation	Plinth of stone and mud	Stone plinth or wooden piling	Earth/stone plinth	Slightly raised platform	Earth/stone plinth
Floor	Compacted earth with fine mud layer	Compacted earth or clay tiles	n.s.	Covered by mud layer made	n.s.
Ceiling	High	High ceilings	High ceiling	High ceiling	n.s.
Openings	Very small	Upper part of exterior wall is made of loose bamboo strips	n.s.	Few and small openings	Few and very small, doors are largest openings

5.2.5. *Roof*

The typical roof type applied in vernacular architecture in the warm temperate climate of Nepal is the pitched roof supported by a timber structure and covered by locally available hatch, stone slates or tiles. A large roof overhang of minimum 50 cm protects the walls from the heavy monsoon rain and avoids solar penetration of the facade during summer [14,16]. In Central Nepal the roofs were typically covered by thatch that lasts properly maintained up to eight years [16]. In Dolakha's Hill houses slate on timber structure is the main roofing material. The pitched roofs of Limbu and Gurung houses are very steep and use thatch, straw or grass as roofing. Newar architecture has developed a water inclusive roof design of burnt clay tiles which are placed upon a mud layer of 4–10 cm [14,32].

5.2.6. *Foundation, floors and ceiling*

Most houses in warm temperate climate of Nepal have a stone foundation that protects from flooding during the monsoon season. The foundation of Newar houses is made of a 60–80 cm deep stone plinth [14,20]. In Indo-Nepalese houses and those studied in Dolakha a 30–50 cm thick stone platform serves as foundation of the building. This platform is often extended about 1.50 m at either one or more sides of the exterior walls to create a veranda which is used as semi open working space. The ceilings are very low (not more 1.80 m) to reduce the air volume that needs to be heated during the cold season. In all studied houses a wooden framework of pillars and beams is used to support the ceilings. It is covered by lathwork and rough casting of 20 cm mud layer and a final layer of a mixture of clay and cow dung [16]. In other houses clay or earth is used for flooring [32]. Wood was widely available in the hilly area and is, therefore, used as structural as well as covering material. The additional use of clay and earth increases the thermal mass of the floor and contribute to balance the diurnal temperature changes.

5.2.7. *Openings*

The openings in houses of Hilly Nepal are rather small, but larger than those in the mountain houses. The windows are mainly located in the longer facade that faces downhill and is mostly oriented southwards. The side and the back wall have often no openings except a small hole from the kitchen which is used as smoke outlet. In Newar houses the main living room has a big window with decorative wood carvings that allows solar radiation of lower angle to heat the room in winter [20] (Fig. 9). Many houses have grilled windows to protect from solar penetration in summer [12]. Remarkable, in Limbu houses the main entry door and larger windows are placed on the shorter facade of the building that is faced southwards [16]. Although most authors describe hilly houses have small windows, compared with mountain houses they are of medium size. The windows are almost always oriented southwards aiming to enhance solar heat gains during winter. The openings are often equipped with shutters that can be closed during cold nights in summer and the cold season. In this way the envelope tightness is increased and the heat losses are reduced.

All studied houses of Hilly Nepal use a large roof overhang to shade south facade and windows. In Indo-Nepalese houses the veranda that is located in front of the longer facade has a thatch covered timber roof structure to provide shading [16]. In the Limbu houses an overhanging timber structure is used to form a veranda surrounding the house in the first floor [16]. The Gurung houses have deep overhanging eaves restrained by brackets [12]. The roof overhang of Newar architecture is widely known because of his decorative character, particularly, in temples and palaces where fine wood carvings can be seen. Moreover, the roof overhang protects the walls from the heavy monsoon rain.

5.2.8. *Results*

It was observed that many building features of the different houses in warm temperate climate of Nepal are largely similar (Table 5). Most vernacular houses have a rectangular floor plan. The longer facade with the openings is often oriented southwards to enhance solar gains during winter. Due to the wide roof overhang the building facades and windows are shaded in summer. In the dense Newar settlements the smart arrangement of courtyards assures solar passive heating in winter and shading in summer. Generally, houses in this climate are of high thermal mass using locally available materials. Particularly, during sunny winter days

Table 5
Characteristics of vernacular houses in warm temperate climate of Nepal.

	Hill house in Dolakha	House in Salle	Newar house	Indo-Nepalese house	Adobe house	Gurung house	Limbu house
Settlement pattern	Scattered	Scattered	High	n.s.	High	Medium	Scattered
Building form	Rectangular floor plan	Rectangular elongated	Rectangular plan with interconnecting courtyards	Rectangular plan along terrace	Rectangular plan	Round shaped	Rectangular form
Building orientation	Longer side southwards	Longer side oriented downhill	n.s.	South, south-east or south-west	Main long façade south-west wards	n.s.	Parallel to river
Stories	2–2.5	2	3–3.5	2	2.5	1.5	1.5–2.5
Internal space arrangement	Ground floor: kitchen and living; 1st floor: sleeping, storage	Ground floor: veranda, kitchen bed and prayer room, 1st floor: bed rooms, storage, balcony	Vertically use of space: ground floor: storage; 1st floor: bedrooms; 2nd floor: living room; 3rd floor: kitchen	Dominant horizontally, 1st floor used as storage, provision of semi-open space	Vertically, ground floor: shop, storage, 1st floor living and bed room, 2nd floor: kitchen	Internally almost open space, few divisions, mezzanine as fodder	More horizontally, ground floor is main living area
Semi-open spaces	Shaded veranda and balcony	Closed veranda and balcony	Courtyard	Open courtyard	No	Veranda	Veranda and balcony
Wall material	Stone, plastered and painted	Stone and mud	Burnt brick (outside), sun dried brick with mortar (inside)	Stone-mud with mud plaster	Adobe wall (sun dried clay bricks)	Wooden lathe covered with mud	Stone and mud, white or ocher mud plaster
Wall thickness	40–50 cm	50 cm	28–70 cm	35–50 cm	50–60 cm	Thin	Thick
Roof material	Stone slates on timber structure	Thatch and stone slate	Burnt clay tiles on mud layer and timber structure	Thatch or slates on wooden roof structure	Burnt tiles on mud layer above timber structure	Thatch on timber structure	Thatch on timber structure
Roof type	Saddleback roof	Pitched roof	Gable roof	Pitched roof	Pitched roof	Steep	Steep pitched roof
Roof overhang	Wide	Yes	Wide	Yes	Wide	Wide	Wide
Foundation	Stone plinth covered by mud/earth	n.s.	60–80 cm deep stone plinth	30–50 cm stonework platform	Foundation of stones	Low plinth	Stone plinth
Floor	Mud layer	Mud/earth covered	n.s.	n.s.	Mud layer	Mud and cow dung	n.s.
Ceiling	Very low, wooden beams and lathwork	Wooden structure with lathwork and mud covering	Wooden beam	Wooden structure with lathwork and mud layer	Structure of timber and bamboo	n.s.	n.s.
Openings	Medium sized	Medium sized openings toward valley side	Small windows, only for living room large window	Small wooden windows on southwards facades	Rather small,	Very small, grilled windows	Medium sized windows

the thermal mass is favorable to store solar heat gains of the day for cooler nights. The low ceiling height reduces the air volume to be heated in the winter season. The vertical internal space arrangement of Newar houses is optimized for the cold winter because it creates buffer zones in the ground and the upper floor in order to keep the main living and sleeping spaces comfortable.

In summary, it can be said that the vernacular houses in Nepal's warm temperate climate are very well adapted to the local climate condition. They consider the most important climate-responsive design strategies like enhancing solar heat gains during winter and protecting from the strong solar radiation in summer.

5.3. Cool temperate climate

Representing vernacular architecture of Nepal's cool temperate mountain climate the houses and settlements of the following tribes and locations were studied and analyzed: Tamang tribe in Langtang region (field research) and Sherpa tribe in Khumbu village [17]. Khumbu village is located in Solukhumbu district in the North of Eastern development region while Langtang is part of Rasuwa district in central region north-west of Kathmandu valley.

5.3.1. Settlement pattern

Settlements in cool temperate climate are denser than those in warm temperate hills. Sherpa villages are mostly built on the beds of old lakes in broader valleys or on sizeable ledges between the mountainside and river gorges [17]. The settlements of the Tamang tribe are compactly built. Several houses are typically attached to each other reducing the exterior wall surface exposed to the coldness (Fig. 11). The streets of Tamang villages are usually paved with stones.

5.3.2. Building form and orientation

Traditional houses in this climate zone have a more elongated form than those in colder alpine climate [17]. Also L-shape can be found. Tamang houses in Langtang region have a compact rectangular shape. Being attached to each other they create a more elongated building volume. If possible the longer façade is oriented toward the sun to enhance solar gains.

The houses of the Sherpa tribe in Khumbu village (Everest region) stand in small groups together on the slopes of a natural amphitheater [17]. Their elongated building volume is generally standing parallel to the slope. Ground floors are partly built into the slope of the hill of mountain behind it (Fig. 10).

Fig. 10. Façade of Newar house with big wood carved window and large roof overhang.

5.3.3. Building stories and internal space arrangement

It was observed that Sherpa as well as Tamang houses have two stories [17]. In Sherpa houses the ground floor is used for storage and livestock, the main living area is situated in the first floor. Tamangs use the upper story for storage of grain and other household possessions, while the elevated ground floor is used as a kitchen, dining place, and bedroom. In Sherpa houses wooden stairs located inside the building lead to the upper floor; stairs in Tamang house are located outside on the main entry facade of the house. Sherpas use the roof partly as terrace with a small shed for lavatory [17]. Tamang houses have usually a balcony on the first floor and a veranda beneath it in front of the main entrance. In all houses the open hearth, normally located in the center of the kitchen, plays an important role because it is not only used for cooking. It is also the only comfortably warm place where the family members can sit during colder nights and in the winter season. The internal vertical space arrangement of these houses leads to thermal buffer zones which have an insulating effect to keep the main living room as warm as possible.

Semi-open spaces play also an important role in Nepal's traditional architectures in cool temperate climate. In front of Sherpa houses an open space or yard is foreseen where newly harvested crops are spread out for drying, are sorted and graded prior to storage and firewood is piled up for winter month [17]. The porch located at the entry to a Tamang house also serves as a protected

Fig. 11. Floor plan and elevation of Sherpa house (after [17]).

Table 6
Characteristics of vernacular houses in cool temperate climate of Nepal.

	Tamang houses	Sherpa houses
Location	Central mountain, Langtang region	Eastern mountain region
Settlement pattern	Attached houses, rather compact	Houses in small groups along the slope
Building form	Compact rectangular floor plan, attached houses	Elongated rectangular or L-shape
Building orientation	Main façade south-west wards	The longer side toward the slope
Stories	2	2
Internal space arrangement	Vertically, elevated ground floor is main leaving area with kitchen and sleeping, 1st floor storage	Vertically, ground floor as thermal buffer space
Semi-open spaces	Veranda and balcony	Veranda
Wall material	Unplastered stonework	Stonework dry or with mud mortar, mud plaster
Wall thickness	40–60 cm	up to 1 m
Roof material	Wood slat weighted with stones, stone slate (if available)	Wooden pillar and beam structure with heavy stone slabs
Roof type	Pitched roof	Pitched roof
Roof overhang	Yes	Yes
Foundation	Elevated ground floor adapting to the slope	Ground floor partly built into the slope
Floor	Wooden lathwork	Wooden floor with carpet
Ceiling	Low ceilings	Double wooden ceiling
Openings	Small wooden windows only in entry facade	Small openings, only one large living room window faced southwards

semi-open space. These semi-open spaces provide another comfortable place, e.g. in winter when the sun is shining.

5.3.4. Walls

Walls are made of locally available stones with a thickness of up to 1 m [17]. Stonework is made either dry or bound together with rudimentary mortar made of soft clayed earth. In Sherpa houses mostly inner and especially outer walls are plastered with clayed earth and then painted because the plaster is also an excellent weatherproofing material. In Tamang houses the outer walls are made of dry stonework while the entry façade of the first floor is made of timber. Inner walls of main living spaces are often planked with timber lathes.

5.3.5. Roof

Due to the heavy rains pitched roofs are more frequently used in the traditional architecture of the cool temperate mountain climate [17]. Either in Sherpa and Tamang houses the roof rest on a wooden pillar and beam structure. Wood or slate (if available) is often used as roofing material in the form of square or rectangular roofing tiles. Heavy stones are placed on top to prevent them from being blown off by heavy monsoon winds.

5.3.6. Foundation, floor and ceiling

The Sherpa houses in Khumbu village are built on a platform which is made of locally available stones. The double wooden ceilings of these houses are supported by a framework of timber pillars and beams. Carpets are often laid above the wooden floor in the main living areas [17].

Tamang houses are slightly elevated attached to each other forming a terrace structure. The interior structure including floors and ceiling are completely made of timber. Often the main entry façade is also timber cladded.

5.3.7. Openings

In Khumbu village doors and windows of the Sherpa houses are faced to south-east direction for an effective exposure to the winter Sun [17]. Also houses in Langtang village are observed to face south-east. No openings are placed in the back side of the houses which are not sun-faced. In Sherpa houses wooden windows with finely carved decoration and colorful paintings. In the main entry façade of Tamang house one decorated small window is placed as opening. The actual opening of those windows is rather small. Often shutters are used to close the openings completely during night and the cold winter season.

5.3.8. Results

The previous analysis shows that traditional settlements in cool temperate climate tend to be more compact than in the warmer climate zones (Table 6).

Locally available stones, which are used for walls and timber, are also the dominating material for floor, ceilings, interior cladding of wall and roofing. Like in warm temperate climate the high thermal mass of the building is favorable to store solar thermal gains during sunny winter days for the cooler nights. Due to the heavy precipitation during monsoon season roofs are pitched and mostly covered by wood slate and stones. Openings tend to be smaller than in warm temperate climate that leads to the reduction of heat losses. Internal spaces are arranged vertically creating a thermal buffer on the upper and lower level for the main living area.

In conclusion, the mountain houses in the cool temperate climate of Nepal are very well adapted to the local climate conditions. They fulfill the most important design strategy – compact building layout and orientation toward the Sun.

5.4. Alpine climate

Representing vernacular architecture of alpine climate, houses and settlements from the following areas in far-western, mid-western, and western development region of Nepal were analyzed: Humla [12,33], Dolpo [16], Upper and Lower Mustang ([11,34], field visit 2010), Thak Khola villages in Mustang district [16] and Manang [12,16]. All these locations are part of the Himalayan mountain range located on the northern stretch of Nepal between 2500 and 4600 m.a.s.l. (Humla – 3500 m.a.s.l., Dolpo – above 4000 m.a.s.l., Upper Mustang – 2800–4600 m.a.s.l.; Lower Mustang – 2500–3800 m.a.s.l., Manang – 3500 m.a.s.l.). In contrast to cool temperate climate, temperatures are lower and the amount of precipitation is very low throughout the whole year.

5.4.1. Settlement pattern

The villages in such a harsh and cold climate are very compact (Fig. 12). The buildings are often attached to each other creating small alleys that are protected from the cold wind and snow storms. In Braga (Manang district) the houses are grouped closely together sharing one or more exterior walls. In Dolpo the houses are also attached to one other but each house has its own outer wall [12]. Thakali villages are observed to be very compact although adjacent walls are not common.

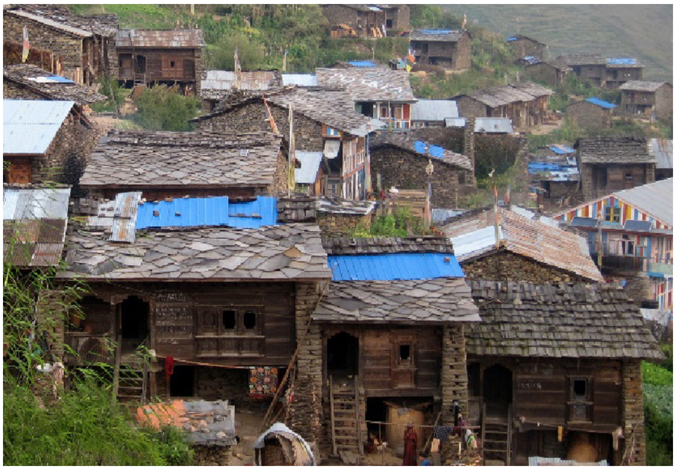

Fig. 12. Typical attached Tamang house with elevated ground floor.

5.4.2. Building form and orientation

Compact building volumes with rectangular building shapes are dominant in Nepal's Alpine climate region [12,16,34]. Many houses in Manang have an almost square ground floor plan [16]. The compact building form reduces the surface-to-volume ratio and, thus, heat losses in this cold climate (Fig. 13). Houses are situated on the southern slope of hills or flat valleys to enhance solar heat gains [16,34]. In this way the high thermal mass of the building can be heated by the strong solar radiation during the day. In Manang closed courtyards are widely used to protect from the cold and strong winds. In Mustang narrow streets and high walls around the buildings marking the pathways have the same function. Other semi enclosed areas like terraces or rooftops are sometimes covered by overhangs or porches to give shade for the strong summer sun [33].

5.4.3. Building stories and internal space arrangement

Mountain houses in Nepal have at least two stories [27]. The analyzed buildings in Humla and Manang as well as typical Thakali houses have three levels [12,16]. The Dolpo houses were found to have two and a half stories [16]. In Upper Mustang two-story courtyard houses are dominant [11]. Multiple stories make the total building volume more compact which reduces the heat losses.

The space arrangement within these houses is mainly organized vertically. The ground and top floor are assigned to secondary use and have the effect of thermal buffer to keep the main living area in the first floor as warm as possible (Fig. 14). Animals are housed in the ground floor leading to increase indoor temperature due to their body heat. The main living area in the second floor is horizontally also surrounded by rooms of secondary use like storage, family treasure, etc. that are creating horizontal thermal buffer zones. In some

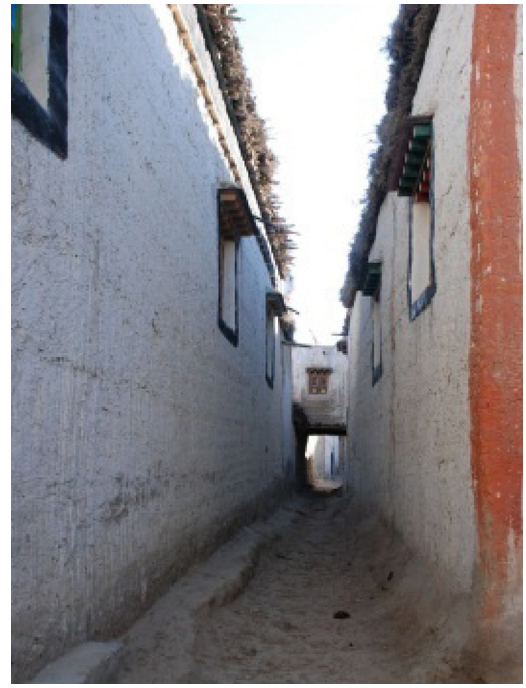

Fig. 13. Narrow lane of compact settlement structure in Upper Mustang.

houses the upper floor contains also a prayer room or a sleeping room for summer [11,12,16].

The flat roofs are forming terraces that are used as open space for any kind of activities during sunny days. The studied shelters of Thakali people in Mustang and in Manang have a small courtyard [16] (see Fig. 14). Being located in a very dense settlement structure the courtyard allows the penetration of day light into almost all inner rooms of the houses.

Semi-open areas play an important role in providing a proper space for working outside of the house during day time. In Humla houses, semi-enclosed areas are built with loose-fitting timber structure in front of each room on the top and middle level [33]. This construction offers some protection from the cold southerly wind. These semi-enclosed areas measure about 6 m^2. Slight overhangs projecting from roofs might also form a semi-enclosed veranda in front of the house.

5.4.4. Walls

The walls are traditionally built of natural stone if locally available. In some areas also sun-dried mud bricks or rammed earth is used [27]. In Humla the studied house has an 45 cm massive wall that consist of thick stones and mud-mortar and is restrained by paired timber beams [12,33]. In Dolpo the ground floor walls

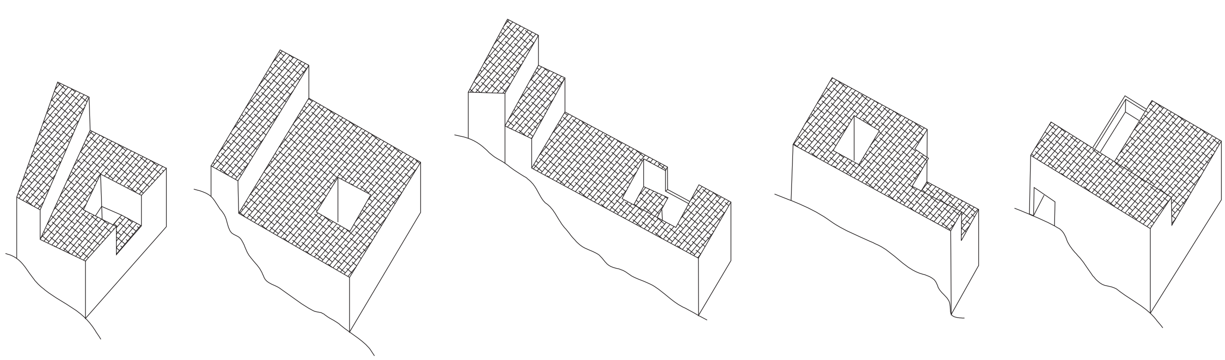

Fig. 14. Compact building typologies of Thakali houses in Marpha, Lower Mustang (after [16]).

are made of stone and mortar with an average thickness of 40 cm while the upper walls are made of lighter sundried bricks [16]. The settlements in Upper Mustang are characterized by mud and mud brick walls [34,35]. Vernacular houses of Thakali people are made of 50 cm thick flat stone masonry that is coated with white and red mud [16]. In summary, all houses are constructed using the most insulating material locally available and have walls of high thermal mass to balance the diurnal temperature range.

5.4.5. *Roof*

Due to the scarcity or even total absence of rainfall roofs of vernacular houses in alpine climate are generally flat [12,16,27,34]. Using locally available material, the roofs are typically made of stone and mud laid on a timber post and beam structure. Vernacular architecture of this region has developed different techniques to make the roof waterproof. For example, in Humla roofs consist of dried juniper branches laid over roughly cut timber boards with an added layer of black mud and a final waterproof layer of fine white mud [12]. This technique protects from the wet snow that typically falls in the early winter months. Thakali and Manang people have also developed a roof finishing system that uses a fine mud layer to ensure waterproofing. Furthermore, wood is piled on the border of roofs that provides protection from the strong wind [16]. In some mountain houses a slight roof overhang can be seen for protecting semi-closed spaces in front of the house [33].

5.4.6. *Foundation, floor and ceiling*

All investigated traditional houses are built above the ground using a foundation made of locally available stones [16]. The structure of ceilings is made of timber posts and beams. The room height is generally very low in order to reduce the need for heating. The traditional houses of Humla have a ceiling height between 1.8 and 2 m; rooms in Dolpo houses are only 1.75 m high [16,33]. Floors are covered by a mud layers over the roughly cut wooden boards [12].

5.4.7. *Openings*

The studied vernacular houses have very small doors and windows made of wood [16,27,34]. Windows are often the most expressive element of the house and have nice carvings with Buddhist symbols [12]. In Upper Mustang villages look like fortified towns due to the reduced window area of the outer walls (Fig. 15). Generally, shutters are used to reduce infiltration of cold air, particularly, during night time. The protection from heat losses is the main bioclimatic strategy to maintain comfortable indoor climate under very cold conditions (Fig. 16).

5.4.8. *Results*

Vernacular houses in Alpine climate have several more features to protect from the coldness than houses in the other climates of Nepal. Settlements and building volumes are compacter and denser than in temperate climates. The houses have far smaller and less openings in order to reduce heat losses. The internal space arrangement is optimized to create thermal buffer zones. The use of window shutters has the effect to increase the tightness of the building.

Roofs are flat as far less rain is falling than in cool temperate climate. The buildings have a high thermal mass that help to balance large diurnal temperature range between the season and in summer. Semi-open spaces like the sunny flat roof top, wind protected veranda and courtyards play an important role to provide comfortable areas for all kind of household activities during the day.

Concluding, the vernacular house design is very much adapted to the local climate conditions. The main objective is to reduce heat losses during long and cold winter season (Table 7).

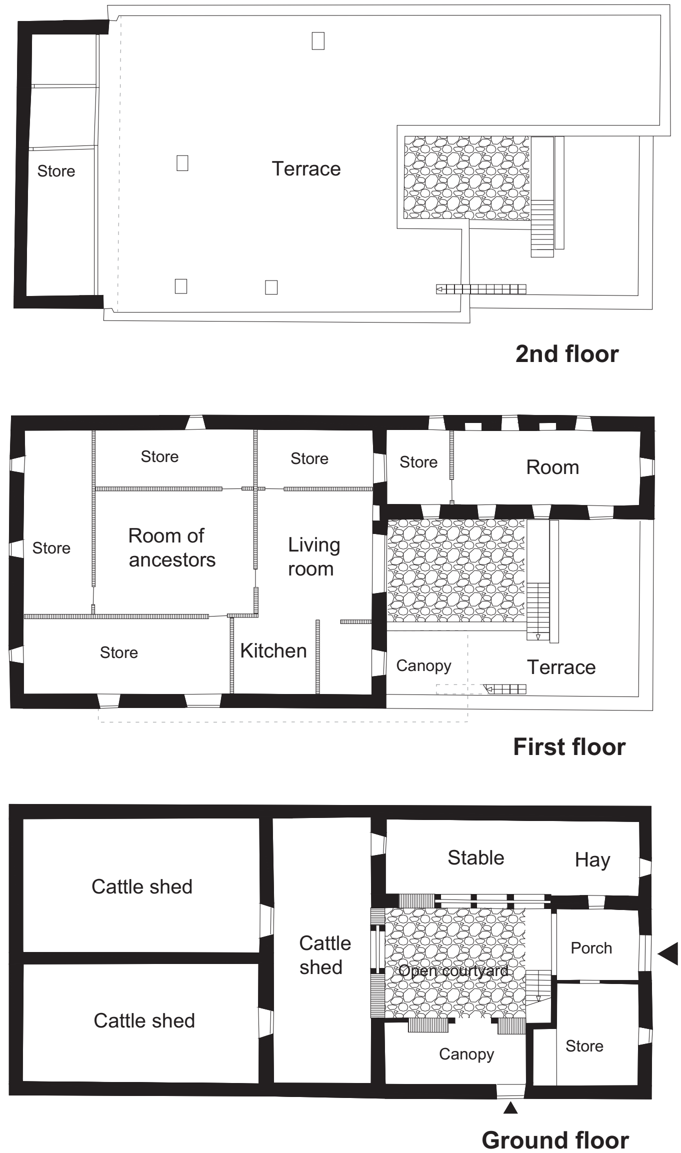

Fig. 15. Floor plan of Thakali house in Taglung (after [16]).

Fig. 16. Typical small windows in building façade in Upper Mustang.

Table 7
Characteristics of vernacular houses in Alpine climate of Nepal.

	Humla house	Dolpo house	House in Upper Mustang	Thakali house	Manang house
Location	Far-western mountain region	Mid-western mountain region	Western mountain region	Western mountain region	Western mountain region
Settlement pattern	Densely scattered, partly attached houses	Houses attached to one other	Dense housing cluster	Compact settlements	Dense, attached houses
Building form	Almost square floor plan	Rectangular	Rectangular toward square	Terraced houses	Almost square surface
Building orientation	South	n.s.	toward sunny side of valley	Southwards facing	Facing south
Stories	3	2.5	2	3	3
Internal space arrangement	Vertically and horizontally use of buffer zones	Vertical space use creates thermal buffer zones	Vertical space arrangement with thermal buffer zones	Centrally and vertically with use of buffer zones	Vertical space arrangement by uses buffer zones
Semi-open space	Roof top	Courtyard, roof terrace	Courtyard, roof terrace	Courtyard, roof terrace	Courtyard, roof terrace
Wall material	Stone and mud mortar	Lower wall: stones and mortar, upper walls: sundried bricks	Sun-dried bricks	Flat natural stone masonry coated with white and red mud	Stone assembled with earth
Wall thickness	45 cm	40 cm	45 cm	50 cm	Thick
Roof material	Mud	n.s.	Mud filling over wooden structure	Severe mud layers	10 cm mud layer on wooden latter
Roof type	Flat	Flat	Flat	Flat	Flat
Roof overhang	50 cm	n.s.	n.s.	Yes	Slight overhang
Foundation	n.s.	n.s.	n.s.	n.s.	Stone, 30 cm deep, 60 cm wide
Floor	n.s.	n.s.	Mud covered	n.s.	n.s.
Ceiling	Low ceilings	Low ceilings	Wooden beam and pillar structure	Wooden structure	Wooden beam and pillar structure
Openings	Small	Very few and small	Small openings in South, West or East facade	Small windows with shutters	Very small wooden windows

Table 8
Climate-responsive design strategies in vernacular architecture of different climatic zones in Nepal.

Climate-responsive design strategy	Climate zones			
	Subtropical	Warm temperate	Cool temperate	Alpine
Solar passive heating	–	+	±	–
Protection from the cold		±	+	+
High thermal mass of walls and floors		+	+	+
High thermal mass with night ventilation	–			
Building orientation north–south	±	±		
Compact settlement and building layout			+	+
Low thermal mass of walls and floors	+			
Light well insulated roof	+	±	±	
Heavy roof				+
Reduction of direct solar heat gain in summer	+	+		
Enhancement of air movement in summer	+	+	±	
Protection from heavy rain	+	+	+	
Outdoor sleeping space for summer	+			
Small openings to reduce heat losses				+
Medium sized openings	±	+	+	
Shading of openings in summer	+	+		

+: applied; –: not applied; ±: partly applied.

6. Conclusion

This study identified many climate-responsive or solar passive design strategies that are applied in vernacular houses of Nepal (Table 8).

Main strategies for subtropical climate of Nepal are solar passive heating in winter, low thermal mass, reduce direct solar gains though building orientation and shading, enhancement of air movement and rain protection. The use of light (low thermal mass) and air-permeable materials for the building envelope and proper placement of openings are enhancing natural ventilation that is essential during warm and humid season. Some but not all houses are orientated north and south as recommended for the reduction of direct solar gains through the façade. All analyzed vernacular houses have adequate shading, semi-opened outdoor spaces for any kind of activities and are protected from heavy rains by a wide roof overhang. Roofs are mostly made of thatch which is a light and well insulating material. Solar passive heating is the only identified bioclimatic design strategies that could not be found in vernacular architecture of subtropical climate.

For the warm temperate climate bioclimatic analysis brought out the following design strategies: solar passive heating for winter, protection from the cold and rain, high thermal mass, enhanced air movement and medium sized windows with shading in summer. These strategies are fully or at least partly applied in the studied vernacular houses. The building orientation toward south as well as the arrangement of courtyards in the more compact Newar settlement enhances solar gains during cold winter and, thus, solar passive heating. However, large roof overhang and shutters keep the steep summer sun away from the building façade to avoid overheating. Recommended high thermal mass of walls and floor as well as light well insulated roof was also found in most studied vernacular houses of warm temperate climate. The courtyard system combined with openings in opposite façades ensures enough natural ventilation in the compacter Newar settlement. While the vertical room setup creates thermal buffer zones to protect from the cold in winter. Shaded semi-open spaces like verandas, balconies and courtyards provide a cooler spaces in summer.

In the cool temperate climate, the building design should be optimized for solar passive heating, protection from the cold in winter, compact settlement pattern and building layout, high thermal mass of walls and floors but light well insulated roof and medium sized. Most of these identified design strategies are applied in the vernacular houses. Heavy very thick stones walls protect the inhabitants from the cold and harsh climate in winter. The arrangement of additional functions like livestock and storage above and below the main living space provides thermal buffer zones. Partly, studied buildings are oriented toward south to benefit from solar heat gains during the day that is stored in high thermal mass of the envelope for cooler night.

Houses in Alpine climate of Nepal need mainly protection from the cold and should enhance solar passive heating. Besides high thermal mass of the walls, floor and roof, a dense and compact settlement structure and building layout is recommended. It was further elaborated that only small openings are suitable. The studied examples of vernacular houses in this climate show few features that would enhance solar passive heating. Priority is given to the protection from the cold through thick heavy walls, very small windows and a very dense settlement structure. Furthermore, the vertical internal space arrangement keeps the main living area with the open fire in the center of the building warm through thermal buffer rooms all around. The flat roof top terrace provides a sunny and warm place for doing any kind of household activity during the day.

The results of this study show that traditional architecture in Nepal is very well adapted to the local climate conditions. The vernacular houses are designed in such a way to provide the most comfortable shelter with the building materials and technologies that were available at that time. The architectural design is optimized to use natural resources like solar radiation and wind efficiently. However, traditional building design and techniques cannot always meet modern living style. Nevertheless, traditional buildings constitute a rich knowledge base that should not be abandoned and totally replaced by modern universal energy-intensive building practices. Instead vernacular design has to be translated and adapted to modern living and comfort requirements. For example, the vertical space arrangement of Newar houses might be inappropriate for modern lifestyle. However, the Newar courtyard settlement structure that is optimized for solar penetration in winter and reduces solar heat gains in summer, can be used to create dense and resource efficient residential areas of modern living.

This study laid the groundwork in identifying the design strategies used by vernacular architecture in Nepal. Further research is needed to translate these traditional strategies into the modern context and come up with appropriate building techniques for the fast developing constructions sector of the country.

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