Student thesis series INES nr 523

Observed hydro-climatic trends and local perceptions of water availability

A mixed-methods study in Marsyandi river basin, Nepal

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2020
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Hanna Ekström (2020).

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Hydroklimatiska trender och lokala uppfattningar om vattentillgänglighet – En blandstudie i Marsyandiflodens avrinningsområde, Nepal

Master degree thesis, 30 credits in Physical Geography and Ecosystem Science
Department of Physical Geography and Ecosystem Science, Lund University

Level: Master of Science (MSc)

Course duration: January 2020 until June 2020

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Acknowledgements

The Crafoord Foundation – For the financial support which enabled the field work in Nepal

Emma Johansson – Thanks for your engagement from the very start, for the balance between constructively critical and supportive discussions. You have really inspired me to think outside the box!

Warm thoughts to all participants in Gaunshahar:
Heaven Hill Academy, kids and teachers – For letting me join your days at school and inviting me for tea, dahl bhat and cucumbers with salt
Sarita Deuja –Thanks for conversations, for your curiosity and for taking your time translating
Abisha Basel Dulal – Meeting you on the first day's bumpy ride was a key moment during the field work. Thank you for taking your time explaining and showing me your part of Gaunshahar.
Shamser Thapa – For facilitating everything practical in Gaunshahar and for your inspiring ideas and work for the kids at Heaven Hill

Two researchers who dedicated time and energy although not being supervisors:
Mine Islar- for initially watering the seeds to this project, as well as for feedback and fruitful discussions along the way
David Tenenbaum- for thorough RHESSys modelling support

Researchers from the other side of the pond:
Milan Shrestha, Arizona State University & Jaakko Putkonen, University of North Dakota - for the generosity of contributing with data, knowledge and insights from Lamjung district and Marsyandi basin

Shangarsha Thapa – for sharing your Nepalese network with me and putting a lot of effort into arranging meetings in Kathmandu
Rojina Shakya – without your help of managing the data access it would have been a very thin thesis
Subash Ghimire – for generously helping me to navigate through the Kathmandu-traffic and the interview sessions

Classmates and friends – thank you for support along the way, we made it!

And Harry – for keeping my tea intakes at constant levels, for sharing your hidden parts of Kathmandu and for constantly believing in me

Abstract

In the central Himalayas, water dynamics are expected to change due to multiple factors like climate change, hydro power development and shifting land use practices. This thesis looks at possible changes in water dynamics in Marsyandi river basin, Nepal, as well as causes to those changes and how they are perceived locally. Grounded in critical physical geography, the study uses mixed methods and an analytical approach of socio-hydrology. Trends in streamflow, precipitation and evapotranspiration from year 1998-2018 were analyzed using climate indices and the Regional Hydro-Ecological Simulation System, and local perceptions were explored through surveys and focus group discussions with households in a mid-hill village, Gaunshahar. The results indicate that the catchment's average annual hydrograph peaked in August with variation in both peak timing within the monsoon season months and volume during the years of study. Evapotranspiration rates on the other hand, were highest in the pre-monsoon season according to the hydro-ecological model, which reached a Nash-Sutcliffe efficiency of 0.51 against observed daily streamflow. Detected climate trends from 1998-2018 include a statistically significant increase in consecutive dry days (2 to 5 days/year), decrease in total precipitation (-26.1 mm/year) and increase in days above 25°C (2 days/year, all *p-value >0.05*). While the focus group participants highlight the importance of a new water pipe system which has increased the security of water supply, there are indications that the pipe system's effectiveness varies within the village. The results prove that the local community has a high dependency on rainfall distribution and spring water availability rather than glacial or snow melt. In combination with the results of increasing temperatures and rainfall intensities over the time period the outcomes show that water availability has been more unpredictable over the course of the study period, but improved water infrastructure has simultaneously lowered the risk of water stress in the local community. For future studies, the Regional Hydro-Ecological Simulation System needs site-specific adjustments of model parameters but shows promising results for application in a Himalayan river basin. Social structures like caste and gender may be important aspects to consider for deepened understanding of the effects on water availability on a local scale.

Key words*: Physical Geography, Ecosystem Analysis, ETCCDI, climate indices, RHESSys, Himalaya, socio-hydrology*

Popular summary

The snow, glaciers and rainfall on mountain ranges provide millions of people with drinking water and act as a reservoir of water for complete ecosystems. Under climate change, melting glaciers in the Himalayas is a commonly known threat to freshwater supply, but there may be other processes affecting water availability. For decision making that secure future freshwater supply, it is important to understand the different causes to changes in water availability.

The aim of this thesis is to look at how water availability is varying and to ask local participants in the mid-hills about their experiences of water availability, as their insights can complement results from climate models and statistics. When combined, we can get a more complete understanding of how water is used and how it is varying.

The study area is Marsyandi river basin, located close to the hiking paths of the Annapurna Circuit, Nepal. It is a diverse area, ranging from the mid-hills of the mountain range to peaks at 8000 meter above sea level. In order to see how rainfall, evaporation and streamflow have changed over the years 1998-2018, trends in measured climate series were calculated. Moreover, evaporation rates were simulated, and interviews and focus group discussions were held with people in a village in the mid-hills, Gaunshahar.

The results show that over the studied 20 years, streamflow in Marsyandi river basin was highest in the monsoon season, most often in August, and that most water evaporated in the pre-monsoon season. Periods without rain have increased with 2-5 days/year over the 20 years as well as maximum temperatures with 2 days/year, but total rainfall has decreased with 26.1 mm/year. In the mid-hills, people highlighted a new pipe system that has made it more secure and less time consuming to get enough water, even in the pre-monsoon season when it is usually more difficult. But the results also indicate that the pipes are not equally accessible for all households, meaning that social structures also effect water availability. By combining climate trends, simulations and interviews, it is clear that people in the mid-hill village of Gaunshahar are heavily dependent on water from rainfall and springs, while at the same time rainfall in Marsyandi river basin comes more unpredictable and drier days are increasing.

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1.Introduction

More than half of Earth's population rely on water that originates from mountain areas (Liniger et al. 1998). With climate change, the effect of increasing temperatures on snow and glacial melt is a major concern, as it is the process that provides large areas downstream with freshwater (Chaulagain 2009). At the same time, mountain ecosystems and livelihoods are likely to see more severe and direct effects of climate change compared to locations at lower elevation, with larger amplitudes of temperature increase at higher elevations (Chaulagain 2009; Parmesan 2006; Pepin et al. 2015). The Himalayas is a region where global warming is predicted to have severe negative effects on glacial melt and precipitation patterns. Even if constraining global warming to 1.5°C as suggested by the Paris Agreement, the Nepalese Himalayas is at high risk of biodiversity loss and unpredictable water availability (Wester et al. 2019).

The mountainous watershed of Marsyandi river basin in central Nepalese Himalayas has been pointed out as a risk area of flooding in case of an outburst of Thulagi glacial lake (Khadka et al. 2019), a risk that also increases with warmer climate. Marsyandi river basin is not only sensitive to changes in climate, but also influenced by hydropower dams, changes in agricultural and irrigation patterns as well as the continuing challenges after landslides provoked by the severe earthquake in Nepal in 2015 (Khadka et al. 2019; Shrestha 2014). These are all factors that may affect the hydrology in terms of river discharge, flooding and groundwater storage, which in turn have potential negative effects on natural resource dependent livelihoods in the area (Chaulagain 2009).

Several studies have focused on the effects of glacial melt (Nakawo et al. 1999; Shrestha and Aryal 2011; Jones et al. 2018; Immerzeel et al. 2013), large scale hydropower dams (Ahlers et al. 2015; Rai 2005) and changed precipitation patterns for the water availability for people living in the lowland plains (Wester et al. 2019; Biemans et al. 2019), but water dynamics in mountain areas where glaciers and hydropower have less direct effects can however be further understood, as the hydrological response of basins highly vary depending on catchment type (Singh and Bengtsson 2005). While the upper part of Marsyandi river basin is glaciated, the annual water budget is dominated by seasonal rain from the Indian monsoon (Kayastha et al. 2019). Within the region areas exist where direct effects from glaciers are less dominant. One such example is the village and farming community Gaunshahar, located on a rain- and spring-fed part of a mountain. Local perspectives can hence contribute with perceptions about water availability beyond the commonly studied topics such as glacial melt and hydropower. In order to enrich the understanding of the whole water cycle in the area and how changes in its dynamics influence water availability within the basin, quantitative modelling and statistical analysis of climate indices from Marsyandi river basin are coupled with participatory methods in Gaunshahar.

With water dynamics being fluctuations of precipitation, evapotranspiration and streamflow and trends meaning continuous upward or downward changes over time, the aim of this thesis is to look at variations and changes in water dynamics and how they are perceived locally, through the following questions:

I. What are the spatiotemporal water dynamics in Marsyandi river basin, 1998-2018?

II. Have there been changes in these spatiotemporal water dynamics, year 1998-2018?
And if so:
What trends in spatial and temporal water dynamics can be identified?

III. How do inhabitants of Gaunshahar mountain community perceive fluctuations in water dynamics and causes of potential changes?

2. Background

Earlier research of spatiotemporal water dynamics in central Himalayas has shown that that the regional hydrology is highly varying from basin to basin, that the climate is linked to global climatic oscillations and that seasonal differences and extreme events are likely to increase with climate change (Immerzeel et al. 2010; Parajuli et al. 2015). The following section goes through environmental research and climate change in the Himalayas, information about the study area as well as the concept of socio-hydrology.

2.1 Water dynamics

The hydrological cycle describes the processes by which water is stored and transported on Earth and in the atmosphere (Figure 1). Four major reservoirs of water can be distinguished in the global water cycle: the oceans, terrestrial water, terrestrial ice and the atmosphere. Oceans are the single largest pool of water on Earth, contributing to around 94-97.5% of the Earth's water (Jones 2014). The largest storage of freshwater on Earth is in glaciers and permanent snow areas followed by the freshwater in rivers, groundwater and the soil, and only a small portion exists as water vapor in the atmosphere.

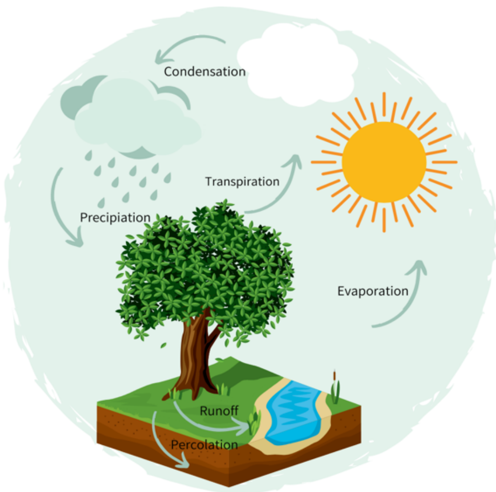

Figure 1. The water cycle with its main processes of evaporation from the ground, the active process of transpiration from vegetation, condensation into clouds and precipitation to the ground where the rainfall creates runoff or infiltrates and percolates further down, *image*: Hanna Ekström, material with permission from Canva Design

In short, the water's pathway through the cycle can be seen as fluxes between the different reservoirs. Water evaporates from the Earth's surface, from water bodies and through plants' transpiration in to the atmosphere, where it cools and condenses into clouds. When precipitation falls as rain or snow, the water infiltrates the soil and contributes to runoff or percolate further down to the groundwater (Jones 2014; Newson 1992). Being a closed circle, the hydrological cycle is thus not altered by climate change in terms of the supply of water. Changes in precipitation and temperature rather redistributes the portions between different reservoirs and fluxes (Jones 2014).

Zooming in to the hydrological cycle of the study area, earlier research has demonstrated that Marsyandi river basin is a dominantly rain-fed area with additional contributions from seasonal snow and glacial melt. Of the annual contributions to runoff, 44 % comes from rainfall, 28 % from baseflow, 15 % from snow melt followed by 13 % from melt of clean ice and ice under debris (Kayastha et al. 2019). In Himalayan catchments in general, the loss by evapotranspiration (ET) from annual discharge is in majority of cases less than 10%, except for densely vegetated watersheds. Marsyandi basin shows an ET negative contribution to annual discharge by 7.7%, indicating that it is a moderately vegetated Himalayan catchment (Bookhagen and Burbank 2010). Annual averages are not telling the complete story however, as both runoff and evapotranspiration have high seasonal variation caused by the monsoon (Bohlinger and Sorteberg 2018). The frequency and intensity of extreme events are further explaining temporal and spatial variation in runoff. In Marsyandi river basin, a decrease in number of rain days but increase in rainfall intensity was seen between 1988 to 2009 (Parajuli et al. 2015). This could mean that although total glacial mass of the Himalayas is expected to decrease, rain dominated catchments like Marsyandi may not be as likely to have decrease in runoff in a near future (Bolch et al. 2012; Immerzeel et al. 2010). It is therefore of high priority to understand variations in rainfall frequency and intensity at catchment scale (Miller et al. 2012). In the next section, we'll take a closer look at how total amount of water fluxes can be modelled at basin scale.

2.2 Hydro-ecological modelling

Within the Himalayan region, water dynamics are highly varying (Immerzeel et al. 2010) and since meteorological stations are scarce, modelling is a commonly used method for hydrological studies (Immerzeel et al. 2013; Nepal and Shrestha 2015; Parajuli et al. 2015). This section aims to describe the general ways in which a hydro-ecological model can used for understanding spatiotemporal water dynamics in a river basin.

The Regional Hydro-Ecological Simulation System, RHESSys, has been developed in a North-American context for modelling water, carbon and nutrient cycles in mountainous terrain and simulates the spatial aspects of a landscape by a landscape object hierarchy (Band et al. 2000). Driven by meteorological parameters of temperature and precipitation the model represents both temporal and spatial variability, which makes it suitable for looking at where and when climate and land use change affects regional scale hydrology.

Thinking back of the hydrological cycle, the major processes can be described with an equation of the water balance:

$$P - E_t + \Delta S = Q \qquad \text{(Eq.1)}$$

Where P stands for precipitation, E_t is evapotranspiration, S the change in storage and Q the discharge. In a hydro-ecological model, measured precipitation is used as input together with temperature which are the two major controlling factors for evapotranspiration (Newson 1992). Built up by equations of the different processes involved in the water balance, the model then simulates the steps of the water cycle that is unknown. As a result, modelled discharge for each day can be compared to observed discharge measurements. While modelling can be used for a wide range of reasons, often investigating possible consequences of future scenarios, the purpose is here to estimate ET, a process of the water balance that is difficult to measure. The way of using hydro-ecological models to estimate unknown processes and how they vary in space within a historical study period has shown to be effective in various areas (Mastrotheodoros et al. 2019; Gonghuan et al. 2018).

Earlier studies in the central Himalayas have indicated that a distributed model, which means one that is based on information from both climate series and a Geographic Information System, GIS (Vieux 2001) is suitable for the highly varying conditions in the Himalayas (Atif et al. 2019) and an important research improvement compared to models driven only by temporal climate series (Litt et al. 2019). RHESSys is a distributed model but by still being parsimonious it can be used in areas where possibilities of data retrieval are limited. In the two following sections, climate and land use factors affecting hydrology are presented.

2.3 Climate in Himalayas and Marsyandi river catchment

The climate of central Himalayas is affected by Asian regional climate oscillations such as the Indian summer monsoon, global climate systems such as the westerlies and the El Niño Southern Oscillation (ENSO) originating from the Pacific Ocean (Bohlinger and Sorteberg 2018; Burbank et al. 2012; Shrestha et al. 1999). While the Indian monsoon and the westerlies control yearly patterns of precipitation amounts and number of extreme events, effects from ENSO can be seen every 4th to 7th year leading to more intense monsoon seasons (Bohlinger and Sorteberg 2018). In Marsyandi river basin, observations confirmed strong correlations between local climate seasonal variation and the Indian summer monsoon (Barros et al. 2000). Four seasons are distinguished, pre-monsoon (March-May), monsoon (June-Aug), post-monsoon (Sep-Nov) and winter (Dec-Feb) (Shrestha 2007). Within the catchment, climate is characterized as subtropical in the south, tropical in the mid-range and alpine to trans-Himalayan in the north with permanently snow-covered peaks (Lillesø et al. 2005).

Apart from the effect on climate from large scale oscillations, microclimatic variations at different elevations are high. A recent study showed that in contrast to neighboring areas such as the Tibetan Plateau as well as compared to global trends, the daily maximum temperature in Nepalese Himalayas is increasing at a higher rate than the daily minimum temperature, 0.04 °C/year compared to 0.02 °C/year (Poudel et al. 2020). Studies have highlighted the effects mountain ecosystems face in global warming scenarios when high elevation sites are warming at higher rates than low elevation sites (Pepin et al. 2015; Baidya et al. 2008; Chaulagain 2009; Shrestha et al. 1999). Mechanisms contributing to the acceleration of warming rate is snow albedo, aerosols, water vapor changes and latent heat release, among others (Pepin et al. 2015). Records of rainfall frequency and intensity on the other hand, indicate high variation across both latitude and elevations (Bohlinger and Sorteberg 2018) which highlights the importance of increased understandings about climate variation on catchment scale.

One way to see indications of climate variations are the core climate indices developed by the Expert Team on Climate Change Detection and Indices, ETCCDI (Peterson et al. 2001). As the climate indices have been widely used in a number of studies they are a useful tool for comparisons within and outside the catchment. The climate indices are further explained in Section 4. Climate is however not the only factor affecting water dynamics, land use and land cover plays an important role of the hydrological cycle, affecting processes like evapotranspiration rates, infiltration capacities of the soil and throughflow of canopies (Newson 1992). In the following section natural vegetation and common land use practices in the study area are described.

2.4 Marsyandi river basin

The study area is Marsyandi river basin (also: Marsyangdi, Marshyandi), a 4805 km² wide sub-catchment to Narayani basin and located close to the Annapurna range, see the satellite image (Figure 2).

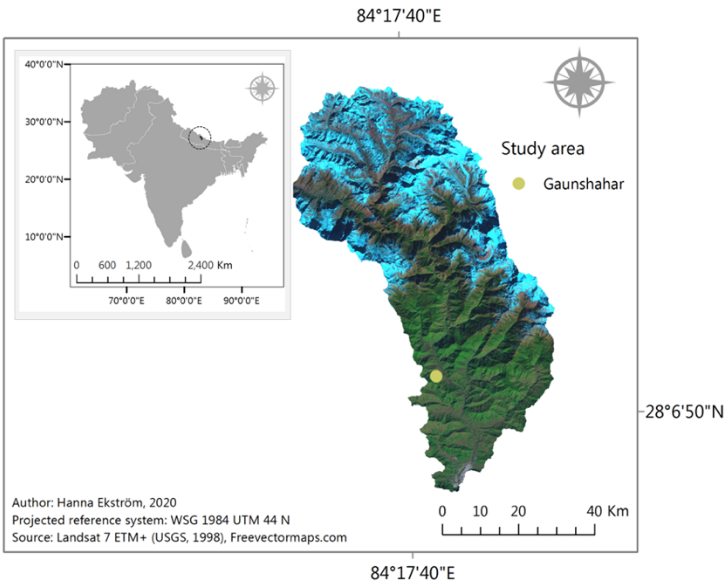

Figure 2. Landsat 7 ETM+ satellite imagery over Marsyandi river basin, located in central Himalayas, Nepal. The upper part of the catchment is permanently glaciated while the lower part consists of forest and agriculture. Gaunshahar, where surveys and focus group discussions are being held, is located in the south-east. Based on data from USGS (1998).

The catchment area's dominating land use type is agriculture, followed by forests and shrubland. Farming is mostly done on smaller rain-fed fields, often in combination with livestock holding, and even more so in the areas of higher altitude (Shrestha 2007). Maize, rice, wheat and barley are common crops, varying with elevation (Shrestha 2007; Aase and Vetaas 2007). Showed by the light blue color in the satellite image, the higher part of the catchment is glaciated, summing up to approximately 13.3% of the total basin area (Dimri et al. 2019).

Marsyandi river originates from the high-altitude mountains and continues out on the plain in southern Nepal. Two major mountain ranges are part of the catchment: the Annapurna-Lamjung Himal range and the Manaslu range with several peaks of about 7000 meter above sea level (m.a.s.l) of altitude (Shrestha 2007). When it comes to natural vegetation, the deciduous Sal (*Shorea robusta*) is the most common tree species in the lower valleys, whereas in the temperate zone mixed deciduous broad-leaved trees such as rhododendron (*Rhododendron arboretum*) and oak (*Quercus llamilosa*) are seen. Coniferous trees exist but are rare. In the higher elevation zone with permanently snow cover and bare rocks, lichens are the main natural vegetation (Dobremez and Jest 1970).

Changes in land use in Marsyandi river basin have in recent years been noted as increased area of agriculture and forest at the expense of shrublands (Shrestha 2014). At the same time, land degradation due to landslides are common in monsoon seasons and was provoked more than usual after the severe earthquake in 2015, which overall strongly affected livelihoods on the mid-hills (Goda et al. 2015).

The majority of the people in Lamjung and Manang districts belong to the Gurung population, with Gurung or Nepali as their first language. Other languages spoken includes Tamang, Sherpa, Newari, Dura and Magar (CBS 2012). The different languages spoken, and religions practiced, is an indicator of Nepal as a country where different caste, ethnicities and community identities mix. Although discrimination based on caste is illegal, historical exclusion from government and administration structures for a large part of the population is still shaping the Nepalese society (Jha 2014; Nightingale et al. 2019). When the community of Gaunshahar is described in continuation, it is important to note that the more or less visible hierarchical structures of caste, gender and age exist on both local, both regional and national scale.

2.5.1 Gaunshahar

Gaunshahar is located on 1330 m.a.s.l, an approximately 45 min drive from the larger administrative center Besisahar, from where a highway connects to the cities of Chame and Dumre (Figure 3 and Figure 4). The village has a total of 6 611 inhabitants in 1 757 households (CBS 2012).

Figure 3. Maize field and houses in Gaunshahar, June 2019. The 8163 m peak of Manaslu hides behind the clouds. *Image:* Hanna Ekström

Figure 4. View from Gaunshahar to a similar neighboring village, located along the foothill of the mountain. *Image:* Hanna Ekström

A high school and a primary school are located in the village. Subsistence agriculture and business in form of small shops are the dominant livelihood strategies and just as in the larger region, rice and maize are the most common agricultural crops. Tourism is another source of income, as Gaunshahar is close to the hiking path Annapurna Circuit and famous for being the place of Lamjung Durbar, a palace belonging to the former king of Nepal. In recent years there has been an acceleration in the rate of out-migration from rural communities, in Gaunshahar as well as in Nepal as a whole, especially of young rural Nepalis moving to urban centers or abroad for military service or education (Nightingale et al. 2019; Korzenevica and Agergaard 2017). Support from migrated family members have been shown as a poverty-reducing factor in Nepal, but it also changes labor structures within families and communities. Because of this, women are playing a larger role in the management and operation of local water and irrigation systems (Wester et al. 2019; Adhikari and Hobley 2015). This is the setting in which water dynamics are studied and in the following section, in order to contextualize the effects of water dynamics, the concepts of water availability and socio-hydrology are defined.

3.Theory and concepts

3.1 Water dynamics and availability

The societal impact from changing water dynamics in Gaunshahar and Marsyandi river basin are coupled to factors like infrastructure, food and rural energy supply from the hydropower sector (Islar et al. 2017). In monsoon season, intense precipitation causes floods, soil erosion and landslides, threatening the infrastructure and food production (Merz et al. 2003). On the other hand, during dry season low recharge of aquifers and little rainfall is a hazard for public water supply and irrigation for agriculture (Merz et al. 2003). Fluctuations in water dynamics and how it affects water availability is important to consider for several important aspects for natural resource dependent livelihoods. Water availability can be seen both in terms of sufficient quantity and quality and has in many rural areas a time aspect, as the time it takes for gathering enough water for household consumption (Iglesias et al. 2007; Rawat and Tiwari 2015). The demand on water supply for agriculture, hydropower and domestic use are some examples of the complex relationship between climate, ecosystems and society. For this reason, next we'll take a look at the socio-hydrological approach for understanding the human-nature relationships of water dynamics.

3.2 Socio-hydrology

A way to understand how the coupled human-nature systems affect and are affected by water dynamics is the concept of socio-hydrology (Sivapalan et al. 2012). Socio-hydrology is a perspective taken to understand the human role in the water cycle. When traditional studies of hydrology look at conservation of aquatic systems and calculations of the water balance (Khamis et al. 2014), social studies on water dynamics are often focused on water use and policy-building (Vörösmarty et al. 2000). Mao et al., (2017) mention this as a common division of the water cycle into a social sub-system and a hydrological sub-system. They are often analyzed as separate systems with separate hazards: the social sub-system is threatened by natural hazards such as changes in precipitation or glacial melt and the hydrological sub-system is threatened by human activity such as hydro power development or increased population. Such a division could be suitable for analytical purposes, but new perspectives and understandings may arise when we look at the ways in which they interact.

Within the framework of socio-hydrology, the aim of this study is to analyze changes of water dynamics as well as drivers and perceptions of such changes.

4. Methodology and data

In order to investigate spatiotemporal water dynamics, trends in these and how they are perceived locally, a mixed methods approach inspired by critical physical geography is taken (Lave et al. 2014). This is done using a combination of climate indices trend analysis, hydro-ecological modelling, focus group discussions and quantitative surveys. The participatory methods such as focus group discussions enable new questions and local concerns to be raised, which can highlight aspects that a visiting researcher may not consider important otherwise (Ackerly and True 2010). By including different gender, age and casts in the discussion, we give attention to power relations and their material effects on water availability (Lave et al. 2014; Mao et al. 2017). The following section starts by introducing the structure of the mixed-method approach, continues by explaining the hydro-ecological model used, the quality check of the data, the modelling and statistical analysis, followed by the field work procedure and qualitative analysis.

4.1 Mixed-methods approach

A combination of quantitative and qualitative methods provides possibility to identify trends and causes to changes from the local to basin scale. The methods used for answering each research question can be seen in Table 1 and a conceptual model of how the mixed-method research is designed is shown in Figure 5.

Table 1. Summary of the methods and data used for each research question respectively.

Research question	*Method & Data*
I. What are the spatial and temporal water dynamics in Marsyandi river basin, 1998-2018?	Hydro-ecological modelling Climate indices
II. Have there been changes in these spatiotemporal water dynamics, year 1998-2018? And if so: What trends in spatial and temporal water dynamics can be identified?	Hydro-ecological modelling Climate indices Focus group and surveys
III. How do inhabitants of Gaunshahar mountain community perceive fluctuations in water dynamics and causes of potential changes?	Focus group and surveys

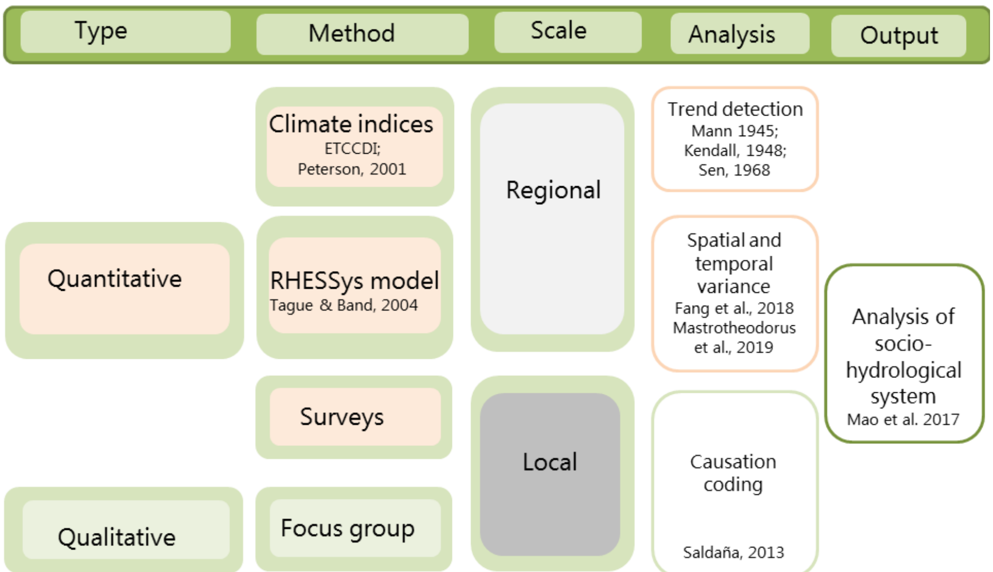

Figure 5. An overview of the mixed- methods used, the scale they are acting on, type of analysis and how they are combined through a socio-hydrological framework built on Mao et al. (2017).

4.2 Model of spatiotemporal dynamics

The Regional Hydro-Ecological Simulation System, RHESSys, simulates processes of water and nutrient cycling at different spatial levels. It is driven by three temporal data sets: daily precipitation, daily maximum temperature and daily minimum temperature, and three spatial data sets: land use, soil texture and elevation. In the following section an overview of the model structure is given; for a more detailed description of the model, see Tague and Band (2004).

RHESSys covers a basin, and it works in daily time steps for a time period determined by the user, in this study a period of 20 years from 1998 to 2018. It is a process-based model which means that the final outcome is a result of several processes incorporated as equations on different spatial levels, see Figure 6.

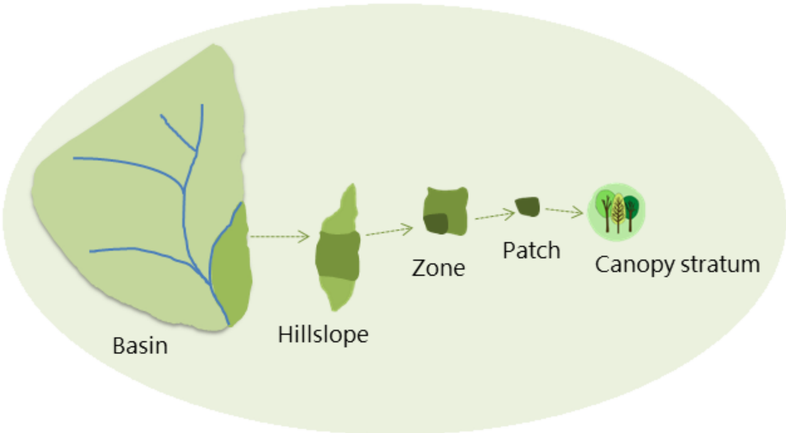

Figure 6. A conceptual model of the hierarchical structure of RHESSys. The basin is the highest-level in the structure, containing several hillslopes that each drain to one side of a stream. Each hillslope contains several zones of different climate, and each zone is built up by small patches of similar soil texture. Finally, vegetation heights in one or several canopy strata is tied to each patch. *Image:* Hanna Ekström, material with permission from Canva Design

The first level of the model is the basin, which covers a closed drainage area. At the basin level, outcomes from smaller spatial units are aggregated. Water entering the stream at basin level is assumed to leave it within one day, which equals to one modeled time step. A basin is divided into several hillslopes, each draining to one side of a stream tributary. Just as for the basin level, output from the hillslope level are aggregated from processes calculated at smaller spatial levels. At the third level, the zones, processes connected to meteorological processes are modeled. A hillslope is divided into zones based on elevation, and each zone is linked to a meteorological station and fed with climate series of daily precipitation and temperature. The fourth and smallest spatial unit in the RHESSys structure is the patch, which is an area with similar land cover and soil characteristics. Linked to each patch is also one or several layers of canopy strata. A canopy stratum is a specific object type where vegetation processes are computed. Several canopy strata can be connected to a certain patch, allowing mixed vegetation heights and compositions at the same location (Tague & Band, 2004).

The modelling of processes is based on three sub-models incorporated in RHESSYS, Biome-BGC, MTCLIM and TOPMODEL. The biogeochemical model Biome-BGC is the base for terrestrial processes (Running and Coughlan, 1988; Running and Hunt, 1993), MTCLIM is used for meteorological processes (Running et al., 1987) and TOPMODEL is used for hydrological processes (Beven and Kirkby, 1979). A more detailed description of Biome-BGC and MTCLIM is given by

Tague and Band (2004) but as the hydrological cycle is the focus of this study, a shorter explanation of TOPMODEL will finalize this section before describing how the data was prepared.

4.2.1 The hydrological model TOPMODEL

Water is treated in two different zones in RHESSys, the unsaturated and the saturated zone. Using TOPMODEL, redistribution between these zones is done with a statistical approach. Based on the topographic wetness index (TWI; see Eq II) TOPMODEL distributes the mean soil moisture deficit (Beven and Kirkby, 1979).

$$TWI = \ln \frac{\alpha}{\tan \beta} \qquad \text{(Eq. II)}$$

TWI is unitless and computed by the natural logarithm of the upslope contributing area, α, of a point divided by the slope in radians, β. In practice, this is derived in a Geographic Information System, GIS, from a digital elevation model. The assumptions behind TWI and the TOPMODEL method is that local topographic slope can be a proxy for water table gradients, that saturated hydraulic conductivity varies exponentially with depth and that a base flux is reached within each daily time step of the model (Tague and Band, 2004). In the following paragraph, available input data are described in detail.

4.3 Climate, soil texture, land use and elevation data

A dataset of climate data from five stations in the lower part of Marsyandi river basin was retrieved from the Department of Hydrology and Meteorology, Nepal. This was complemented with 15 stations from a meteorological network that was managed in the Annapurna range area between the years of 1999-2004 for a study by Putkonen (2004; personal communication 2020-02-05). Out of the 20 stations, 17 stations had recordings of daily maximum and minimum temperature. All stations recorded daily sum of precipitation, however differing in length of the time series and only one station had a coverage of the whole study period (Table 2). After quality check and homogenization 13 stations were kept for further analysis, in order to reduce the risk of overparameterization of MT-CLIM, the sub-model that simulates meteorological processes (Tague and Band, 2004). Measured streamflow for model calibration was available from year 2000 to 2015, at Marsyandi Bimalnagar station, latitude: 28.2°, longitude: 84.4°. The location of the hydrological station and final 13 meteorological stations are shown in Figure 7.

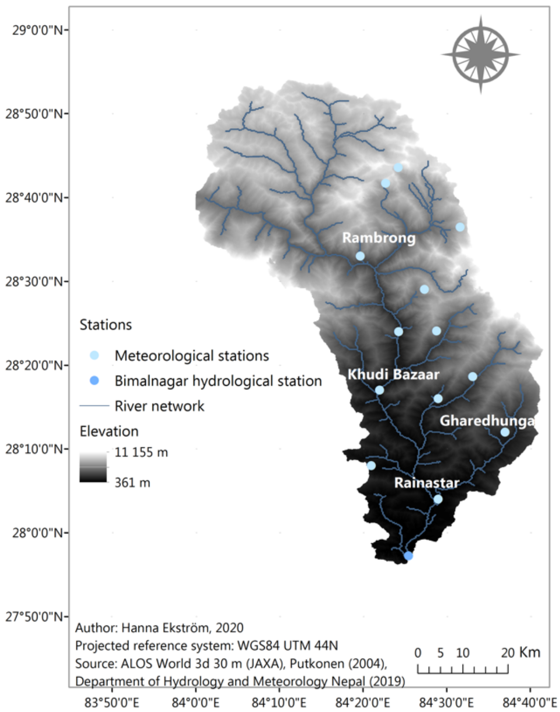

Figure 7. Location of the final 13 stations in Marsyandi river basin used for modelling and labeled with names are the four stations used for statistical analysis of climate indices. The Bimalnagar hydrological station is located in the southern part of the catchment, where recorded streamflow is measured. Data provided by Department of Hydrology and Meteorology (2019) and Putkonen et al., (2004).

Table 2. Climate series from the 20 stations available, five stations from the Department of Hydrology and Meteorology, Nepal, and 15 stations from the underlying data of a study by Putkonen (2004). Parameter and years of period coverage is shown for each station. Stations in italic were only used for initial quality check and homogenization.

Station	*Lat*	*Long*	*Elevation (m.a.s.l)*	*Daily precipitation*	*Daily tmin*	*Daily tmax*
Khudi Bazaar	28.28333	84.36666	823	1998-2018	1998-2018	1998-2018
Faleni	28.26666	84.48333	1300	2007-2018	-	-
Gharedhunga	28.20000	84.61666	1120	1999-2018	-	-
Kunchha	28.13333	84.35000	855	1999-2018	-	-
Rainastar	28.06666	84.48333	548	2007-2018	-	-
Danfedana	28.72638	84.40361	4194	1999-2004	1999-2004	1999-2004
Ganpokhara	*28.32277*	*84.36055*	*2120*	*1999-2004*	*1999-2004*	*1999-2004*
Khudi	*28.52527*	*84.40972*	*820*	*1999-2004*	*1999-2004*	*1999-2004*
Koprung	*28.60638*	*84.36305*	*3133*	*1999-2004*	*1999-2004*	*1999-2004*
Paiyu Khola	28.31027	84.55222	993	2000-2004	2000-2004	2000-2004
Pasqam village	28.39972	84.40472	1702	2000-2003	2000-2003	2000-2003
Probi	28.60750	84.52694	1495	2000-2004	2000-2004	2000-2004
Purano village	*28.36888*	*84.37972*	*1787*	*1999-2004*	*1999-2004*	*1999-2004*
Purkot	*28.23388*	*84.51138*	*528*	*1999-2003*	*1999-2004*	*1999-2004*
Rambrong	28.55	84.32833	4435	1999-2004	1999-2004	1999-2004
Sundar	*28.43611*	*84.50944*	*3823*	*1999-2004*	*1999-2004*	*1999-2004*
Syange	28.48361	84.45611	1200	1999-2004	1999-2003	1999-2003
Tal	*28.46722*	*84.49055*	*1600*	*1999-2004*	*1999-2004*	*1999-2004*
Telbrung	28.40111	84.48027	3168	1999-2004	1999-2004	1999-2004
Temang	28.69472	84.37861	2760	1999-2004	1999-2004	1999-2004

As basis for making a land use classification, a Landsat 7 ETM+ imagery from the 13th of December 1999 was retrieved, corresponding to the tiles of Marsyandi river basin located at path 142, row 40 and 41 in the Worldwide reference system used for Landsat products (U.S. Geological Survey, USGS 2018). A vector file of classified land use for the lower part of the catchment, Lamjung district, was used as initial reference data (Shrestha 2007). Information about soil texture was retrieved from a digital soil database of the Nepal Soil Science Society (NSSS, 2015). Elevation data were retrieved from the ALOS Global Digital Surface Model (AW3D30), a 30-meter global resolution dataset, produced from images collected by the Panchromatic Remote-sensing Instrument for Stereo Mapping (PRISM) aboard the Advanced Land Observing Satellite (ALOS). AW3D30 has shown to have high accuracy in relation to other freely available data sets with similar resolution, such as SRTM and ASTER GDEM (Boulton and Stokes 2018; Courty et al. 2019; Nadi et al. 2020; Santillan and Makinano-Santillan 2016) and is available from the Japanese Aerospace Exploration Agency (Tadono et al. 2016). A summary of the available soil, land use and elevation data are shown in Table 3.

Table 3. A summary of the spatial data sets: soil texture, satellite image used for land cover classification and digital surface model for elevation data.

Data type	*Year*	*Spatial resolution*	*Source*	*Provider*
Soil texture	2015	30 m	Soil Science Division, NARC	NSSS (2015)
Land cover	1999	30 m	Landsat 7 ETM+	USGS (2018)
Elevation	2016	30 m	ALOS, PRISM	JAXA (2016)

4.4 Data preparation for spatiotemporal modelling

As described above, RHESSys needs a minimum of three complete temporal series (daily maximum temperature, minimum temperature and daily sum of precipitation) and three spatial data sets (land use, soil texture and a digital elevation model) in order to work. This section describes the preprocessing of the six different data sets to be used as model inputs.

4.4.1 Climate series: quality control and descriptive statistics

The climate series are made up of daily minimum and maximum temperature as well as daily sum of precipitation, from initially 20 stations in Marsyandi river basin. In this section the treatment of missing data and outliers is explained through the homogenization process that resulted in 13 stations kept for further analysis.

Homogenization of climate series

As initial data check, missing data in the climate series were noted and the data distribution was plotted in Quantile-Quantile-plots in R 3.6.3 (Lee et al. 1998; Singh and Qin 2019; R Core Team 2020), showing positively skewed distributions for the precipitation series from all stations, as expected since rainfall records below zero are unlikely. Apart from coordinates and elevation data for each station, there was a lack of additional information about reasons for breaks in the time series, which required a homogenization method that functions although not having metadata.

The chosen homogenization method, Climatol, is a tool developed by the Spanish State Meteorological Agency for R (Guijarro, 2011; Mamara et al., 2013). It has shown proof in effectively detecting major breakpoints in climate series by using the Standard Normal Heterogeneity Test, SNHT, and correcting for inhomogeneity by filling gaps (Alexandersson 1986; Costa and Soares 2009; Mamara et al. 2013). Climatol has a high tolerance for missing data in a series, as it computes a reference series based on a weighted average of nearby stations. This method however comes with a risk of filling gaps using data from a close but climatologically different station (Mamara et al., 2013). The risk can be reduced by preparing sub-groups of correlated stations (Guijarro, 2011). A correlation analysis between all 20 stations and k-mean clustering was done to see the number of suitable sub-groups, resulting in two groups. The climate series were then homogenized with the station Khudi Bazaar, that had the longest recorded consecutive climate series of the stations, included in both groups. The choice of final stations to include was based on elevation spread, spatial distribution and correlation. Stations with very high correlation to another station was discarded, to minimize the risk of overparameterization of the MTCLIM sub-model within RHESSys. Based on earlier research, including several climate stations with very similar values is going to add complexity to the interpolation process without significantly changing the forcing and input of water to the simulation (Band, 2000; personal communication Tenenbaum, 2020-06-15).

Precipitation

As precipitation series are expected to have a non-normal distribution, the normalization within Climatol was done based on ratios rather than absolute differences (Mamara et al., 2013). This normalization technique is in statistical means similar to a type II linear regression, which allows pairs of climatological series to be compared. In the common type I linear regression, the main focus is to minimize errors vertically between a data point and the regression line of the series, whereas Climatol uses a method where the goal is to minimize error perpendicular to the fitted line (Mamara et al., 2013). The homogenized series of daily sum of precipitation was finally analyzed for trends in R (R Core Team 2020).

Temperature

Before the homogenization through Climatol, missing temperature-series are estimated using lapse rate. Monthly average temperatures based on year 1999-2004 for the Annapurna stations are correlated against elevation and show thoroughly negative correlation (-0.99 ± 0.005). The relation between elevation and temperature at the mid-elevation Khudi Bazaar and high elevation Rambrong stations from 1999-2004 is used to generate a linear regression model of basin wide environmental lapse rate (Garcia et al.,2013). With the lower of the two stations, Khudi Bazaar, as reference base station, gaps in the series of the remaining stations are then filled based on the calculated lapse rate and elevation. Finally, the complete temperature series from the whole catchment are homogenized through Climatol using the same procedure as for the precipitation series. An exception is that since temperature series can be both positive and negative, the normalization is done using absolute differences instead of ratios (Costa and Soares, 2009).

4.4.2. Land use

A land use map is the base for the patches and canopy stratum layers of RHESSys, where processes like precipitation throughfall and infiltration are calculated (Tague and Band, 2004). The goal of the preprocessing was to get a land use map from a satellite image with a number of classes that could i) represent variation in land cover that affects the different hydrologic processes in the basin and ii) be mapped with confidence based on the available data. Based on these criteria, the satellite data was mapped into five land use classes: forest, shrubland, agriculture, barren land and snow. Since two areas of clouds were visible in the image, clouds were included as a class for the supervised classification but was later on interpreted manually as areas of barren land. The two tiles were mosaiced in ArcMap (Esri, 2016) and training sites of the different land use classes were chosen, with support from high resolution MAXAR imagery (Google Earth 2019). The technique may be used when field conditions limit the possibility of sampling of ground control points, in this case as field work is conducted in monsoon season (Vittek et al. 2014; Bagan et al. 2010).

Classification of the satellite image was done using random forest classification in the *randomForest* package in R 3.6.3 (R Core Team 2020). Random forest is a classification method based on machine learning, proven to effectively classify land cover types based on a training set of spectral signals from a satellite image (Pal 2005; Li et al. 2014). The method is built up on an ensemble of predictive models, so called decision trees. After training the predictive models on known pixels from each land use class, each decision tree provides a classification of the pixels in the image. The strength of the random forest algorithm is that is takes the results, or votes, from the whole group of decision trees' and choose the classification that gets most votes. After classification, accuracy assessment was done based on a stratified random sampling of 1000 samples. The final land use classification had an overall accuracy of 89%, a Cohen's Kappa of 82% and user's and producer's accuracy according to Table 4. For statistical explanations see Supplementary text SI.

Table 4. Accuracy assessment of land cover classification generated by random forest classification. Forest and snow are the most accurately mapped land cover classes, in both measured of user's and producer's accuracy. The Cohen's kappa is 82%.

Class	*I*	*II*	*III*	*IV*	*V*	*VI*	*Total*	***User's Accuracy***
I. Forest	573	15	0	0	0	3	591	**0.97**
II. Shrubland	20	41	0	0	7	7	75	**0.55**
III. Snow	0	0	169	0	0	0	169	**1.00**
IV. Clouds	0	1	2	3	0	1	7	**0.43**
V. Agriculture	0	5	0	0	77	11	93	**0.83**
VI. Barren land	0	6	0	20	11	28	65	**0.43**
Total	593	68	171	23	95	50	1000	
Producer's Accuracy	**0.97**	**0.60**	**0.99**	**0.13**	**0.81**	**0.56**		**0.89**
Kappa	**0.82**							
OA	**0.89**							

4.4.3 Soil texture

Soil texture provides necessary information about the permeability of a specific patch in the model structure. Data from Nepal Society of Soil Science (2015) was georeferenced based on a vector file of Lamjung district (Shrestha 2007) resulting in a total Root Mean Square Error value of 0.002. The information was then digitized, and four final soil texture types were mapped: Clay loam, loam, loamy sand and sandy loam. Metadata for the soil texture was not available.

4.4.4. Digital Surface Model

A digital surface model (DSM) is used to generate the levels of basin, hillslopes, zones and patches within RHESSys. The DSM was checked for artificial sinks and filled with D8 analysis in ArcMap(Esri 2016), a method where flow from one cell is directed to any of the eight neighboring or diagonal cells with the largest difference in slope (Tarboton et al. 2009). The filled DSM was run to create flow accumulation and flow direction, with the final goal to generate a linked stream network in the study area (Tague and Band 2004). The threshold value for stream generation of flow accumulation was set to 250 contributing cells, proven suitable for a similar case in India with highly varying terrain and 30 m resolution DSM (Paul et al., 2017). To validate the generated stream network, it was overlaid and seen to delineate the stream network of a high resolution CNES Airbus imagery from 18th of Nov 2017 (Google Earth 2017). Apart from a stream network, slope, aspect and the watershed delineation were needed, and these three layers were also derived from the filled DSM in ArcMap (Esri 2016). For the level of zones, the watershed needs to be divided into areas with similar climate. Since elevation has a strong relation to temperature and precipitation (Baidya et al. 2008), the division into zones was made based on the elevation of the meteorological stations. Elevation bands were created, taking the midpoint of elevation between each station pair. The filled elevation layer, soil texture and land use/land cover map are seen in Figure 8.

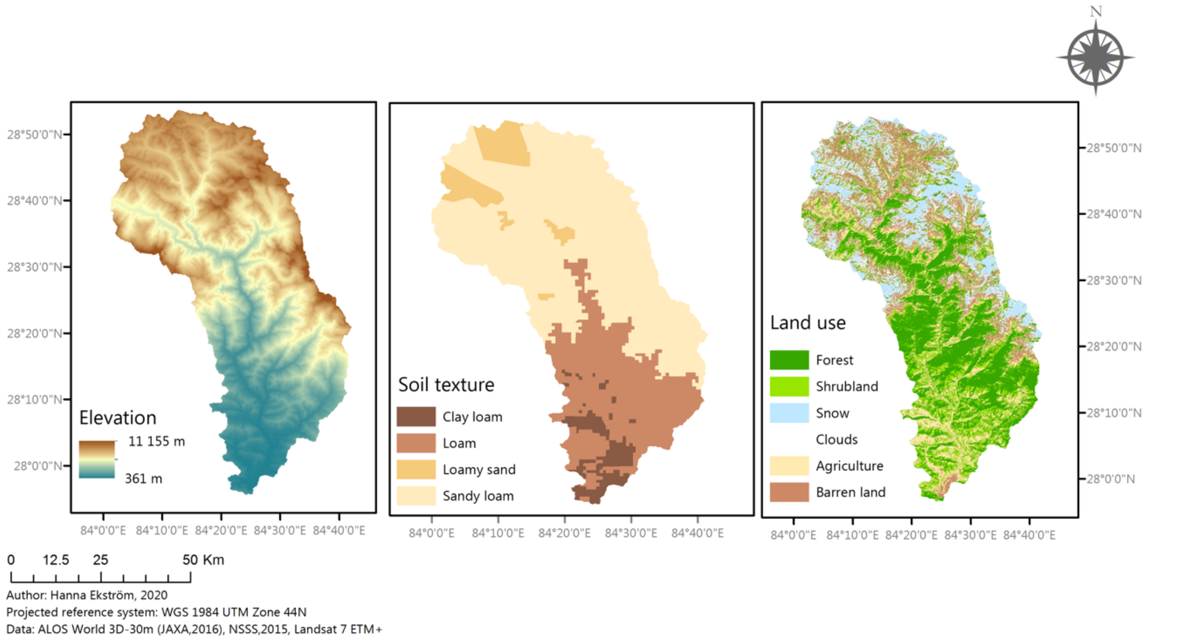

Figure 8. The three different bases of input layers to RHESSYS include elevation data from a digital surface model with 30 m resolution (JAXA, 2018), soil texture types (NSSS, 2015)and a classified land use/land cover map based on a Landsat 7 ETM+ from 13th of December 1998 (USGS, 1998).

4.5 Modelling spatial and temporal water dynamics in Marsyandi

With all data sets prepared, a world file that combines all input data was prepared through the package *RHESSysPreprocess* in R (Burke 2020; R Core Team 2020). Before calibration a spin-up run is strongly advised, where pools of nutrients and water is filled up to a state from where it is realistic to start a simulation (Tague and Band 2004). Data from October 2003-September 2008 was used iteratively over a 100 year-period for model spin up. The chosen years represent both drier and wetter, colder and hotter years in order to make the spin-up run go through all possible variation within the data. After spin-up, the model was calibrated by changing two multipliers to the soil parameters of soil hydraulic conductivity, *m*, and surface saturated hydraulic conductivity, *K*. Random search for the optimal values of the two parameters was applied, by combining m and K in the ranges of m= 0.01-10 and K= 1-100. The outcome was compared against observed streamflow of Bimalnagar hydrological station from five years, 2003-2008 and Nash-Sutcliffe Efficiency (NSE) was calculated. NSE is a measure of the model's ability to predict observed values and is commonly used for validating hydrological models. It ranges between negative infinity to 1, where the closer the model is to 1, the better correlation with the observed data and a value below 0 means that the mean of the observed data is a better predictor than the model (Nash and Sutcliffe 1970; Moriasi et al. 2007). There is no consensus for what value of NSE that is acceptable for a hydrological model, but based on literature an NSE value larger than 0.5 is considered acceptable for a model on daily time step (Moriasi et al. 2007). After calibration and validation against the whole available period of observed data, 2000-2015, RHESSys was run over the period from 1998-01-01 to 2018-12-31.

4.6. Climate indices and trend analysis

Four of the station's series were after homogenization chosen for calculation of a selected subset of the climate indices developed by the Expert Team on Climate Change Detection and Indices (ETCCDI; Peterson et al. 2001), see Table 5. The climate indices effectively summarize trends in precipitation and being widely used they are a useful tool for linking the results of the current study to a broader context (Turco and Llasat Botija 2011; Baidya et al. 2008; Manandhar et al. 2012; Karki et al. 2017; Poudel et al. 2020). The four stations, Khudi Bazaar, Rainastar, Gharedhunga and Rambrong, were chosen based on the criteria of having long consecutive series of recorded daily precipitation while at the same time representing diversity in latitude and elevation within the catchment.

Calculation of the climate indices was done in the R package *Climdex* (Bronaugh 2020). Monotonic upward or downward trends in the climate series over the time period were estimated using the non-parametric Seasonal Mann-Kendall trend test from the *Kendall* R package(McLeod 2005), as seasonal dependence is expected, followed by Theil Sen's Slope estimator for calculating the magnitude of trend from the *trend* package (Pohlert et al. 2016; Sen 1968). The Mann-Kendall trend test is a non-parametric method for linear regression analysis, chosen for its ability to detect trends in non-normally distributed data by comparing relative magnitudes rather than actual data values (Gilbert 1987). It tests for a consistent positive or negative trend in the time series and is widely used in hydrological time series analysis (Mann 1945; Poudel et al. 2020; Kendall 1948).

For the index of monthly highest amount of rain during a 5-day period, RX5DAY, a different version of the Mann-Kendall test was used. As the series beforehand are separated in seasonal data sets and therefore not expected to show seasonal dependence within each data set, but still likely to have autocorrelation, trend detection was done using the block bootstrapped Mann-Kendall trend test. The reason for this is that autocorrelated series with linear trends are a common assumption for hydrological time series, and block bootstrapping provides a powerful way to correct for autocorrelation but in comparison to other correction methods is less prone to under- or overestimating trend detection (Villafuerte et al. 2014).

Table 5. Summary and description of the used subset of ETCCDI:s core climate indices used to analyze precipitation extreme events (Peterson et al. 2001). The indices count of days with more than 20 mm of rainfall(R20mm), consecutive dry days (CDD) and consecutive wet days (CWD) indicate trends in precipitation frequency, while the indices of total precipitation (PRECTOT), simple daily intensity (SDII) and maximum amount of precipitation during a five day-period (RX5DAY) show trends in rainfall intensity.

Index type	*Index*	*Description (unit)*
Frequency	*R20mm*	Annual count of days when PRCP≥ 20mm (days)
	CDD	Consecutive Dry Days (days)
	CWD	Consecutive Wet Days (days)
Intensity	*PRECTOT*	Total precipitation in wet days (mm)
	SDII	Simple daily intensity index, average precipitation amount on a wet day (mm/day)
	RX5DAY	Monthly highest precipitation amount in a five- day period

4.7 Local perceptions of water dynamics

At the initial stage of the study, interviews with professors in hydrology and sedimentology was done at Kathmandu and Tribhuvan University, and with members of the NGO Dalit Alliance for Natural Resources (DANAR). The interviews served to gain knowledge about different perspectives on water dynamics at national and regional level, but these interviews were not used for further analysis.

4.7.1 Surveys and focus group discussion

In the village Gaunshahar, household surveys were done as a first step (Supplementary text SII). Additional notes were taken when surveys opened up for longer discussions. In total, 54 questionnaires were answered by participants in the age of 19 to 80. Different translators supported in different situations: students from the higher grades of the primary school, a teacher and sometimes a family member of the interviewee. The translators were the ones choosing the participating households, often clustered in a neighboring area. A note on the household's location within the village was taken, but the exact location and names of the participants were not noted. Choosing to work with different translators meant that in total, the locations of household surveys were spread out from locations at lower to higher elevations within the village, and at different distances from the river and water pipes.

Figure 9. Focus group discussion before an already planned micro-finance meeting with members of the microfinance group in Gaunshahar, 22nd of June 2019. *Image:* Hanna Ekström

The focus group discussion was held in combination with an already planned microfinance-meeting, which gathered in total 18 participants: 17 women and one man. Combining the workshop with a meeting like this meant that a suitable size of the target group of active farmers and business owners was gathered, at a time when they had already planned not to be in the fields. Questions for the focus group were prepared around the topics of where and how water was achieved, if there had been changes in water access and reasons for limited water availability, with the discussion kept open ended in order for allowing participants to put emphasis on the topics they wanted to highlight. The question form for the focus group discussion can be seen in Supplementary text SII.

4.7.2 Analysis of perceptions and identifying causes

With the goal to see the participant's perceptions on possible changes in water availability and drivers of such changes, the qualitative data was first coded using causation coding (Saldaña, 2013). Causation coding is a technique where causal links of the type "*condition→ link→ outcome*" are noted and analyzed. Sometimes they come from a direct question: "*why do you think there is more water now compared to before?*" and at other times words such as *therefore, because*, in the participant's explanations can be used as clues to see how participants talk about causes (Saldaña, 2013). Commonly mentioned causes and effects could then be ordered in themes around their topics. In order to keep an iterative and exploring research design, themes seen in the qualitative data worked as foundation for analysis of the quantitative data, e.g. the concept of seasonality mentioned in the interviews and later on explored in the statistical analysis of the climate series data. Finally, the socio-hydrological framework served as a base for grouping the results from climate trend analysis, modelling and participatory methods to see causes to fluctuations in water dynamics on different scales.

5.Results

In the following section, water dynamics in Marsyandi river basin between year 1998 to 2018 identified through trends of climate indices and hydro-ecological modelling are shown, followed by local perceptions about changes in water dynamics and causes to changes.

5.1 Spatial and temporal water dynamics in Marsyandi river basin

Through hydro-ecological modelling and statistical analysis of observed climate data the results confirm that water dynamics in Marsyandi river basin are strongly influenced by seasonal precipitation patterns, with the annual hydrograph showing a close to gaussian distribution over May to November, with a peak of discharge in August. Moreover, the output indicates that the daily average discharge per month has high variation within the study period. Negative trends in total precipitation was seen but precipitation patterns are highly varying within the catchment, both according to modelled and observed data.

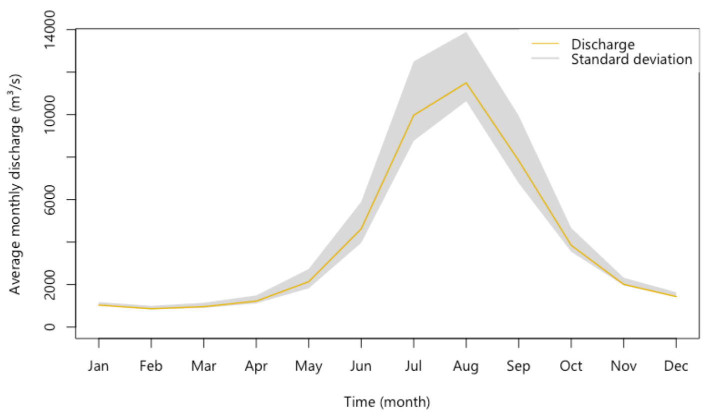

Figure 10. Average monthly discharge (m^3/s; yellow line), and standard deviation (grey area), based on observed values from Marsyandi river, Bimalnagar hydrological station year 2000-2015. Data provided by Department of Meteorology and Hydrology, Nepal (2019).

The annual hydrograph based on monthly sums of discharge in Marsyandi river basin shows increased average discharge rates from May to November, corresponding to monsoon and post-monsoon seasons. The data is based on observed streamflow, year 2000-2015 at the hydrological station Marsyandi, Bimalnagar (Figure 10).

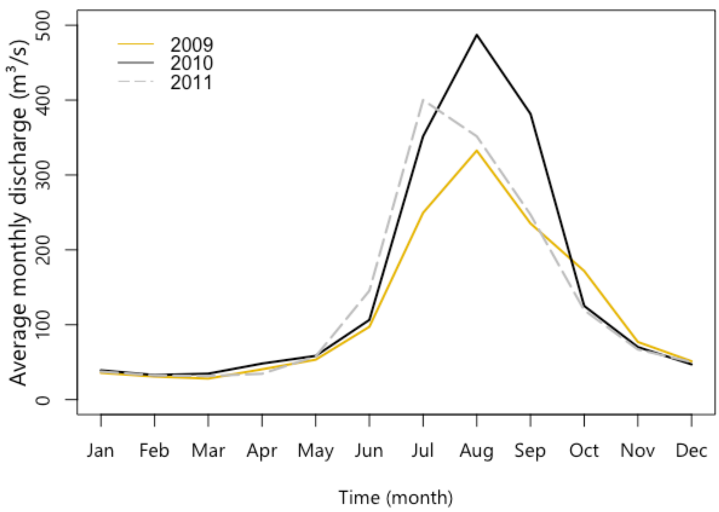

Figure 11. Hydrographs from year 2009-2011 representing temporal variation in the water dynamics of Marsyandi river basin. Data from Department of Meteorology and Hydrology Nepal (2019).

The runoff to discharge within the catchment varies from year to year in the study period. The years 2009-2011 are examples of variation in time and volume of average daily discharge per month, where the year 2009 had a small peak in average daily discharge (320 m^3/s; yellow line) , whereas year 2010 reached up to 487 m^3/s as an average daily value for August (black line) Year 2011 was one of few years where the peak was shifted to July instead of August (grey line) (Figure 11).

After validation against the modeled streamflow, RHESSys shows a Nash-Sutcliffe efficiency of 0.51. The model captures the order of magnitude of the average streamflow and the yearly timing of peaks in discharge (Figure 12). But it underestimates streamflow in winter and post-monsoon seasons and is poorer in describing the variation in amplitude of the discharge during monsoon.

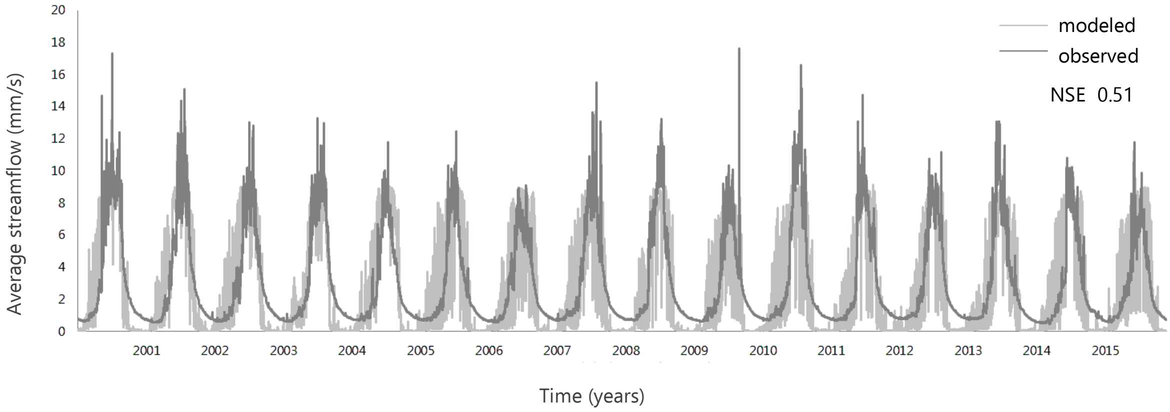

Figure 12. Observed discharge measured at the outflow of the catchment, Marsyandi Bimalnagar hydrological station (Department of Meteorology and Hydrology 2019)

The average peak in annual evapotranspiration rates is, according to RHESSys output, in the pre-monsoon season and thus before the peak of discharge (Figure 10). The small standard deviation of the average evapotranspiration rates over the study period indicates, similarly to the graphical comparison of streamflow, that the model outcome did not vary much between years. Spatially, evapotranspiration rates are highest in the southern parts of the catchment where agriculture, forest and shrubland are the dominating land cover types (Figure 11).

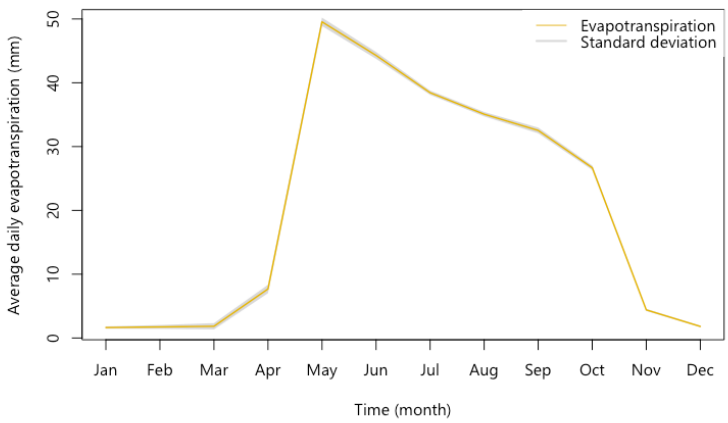

Figure 13. Average daily evapotranspiration per month(yellow line) with standard deviation of 0.17-0.64/month (grey shading), based on RHESSys modeled outcomes of evapotranspiration rates, 1998-2018.

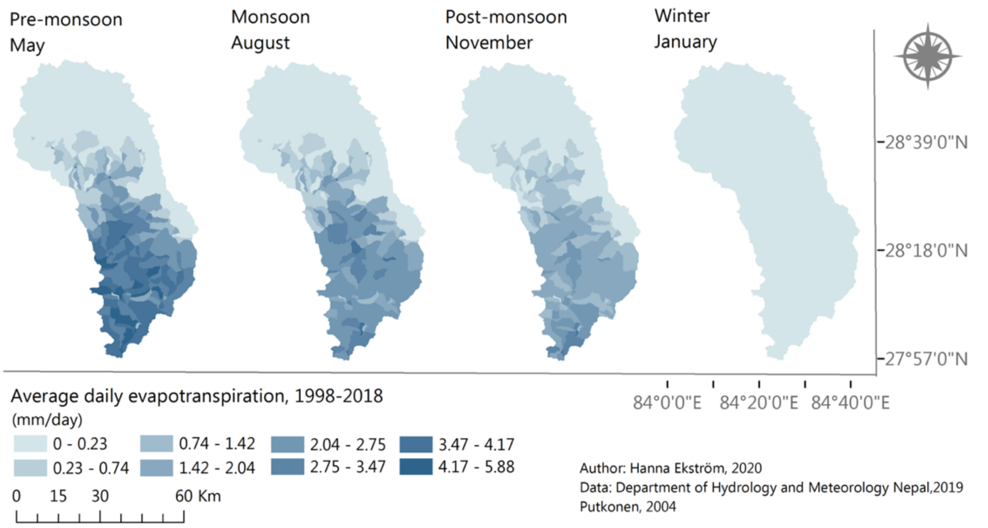

Figure 14. Average daily evapotranspiration rate for one month per season, from the RHESSys modeled outcomes, based on data from Marsyandi river basin, year 1998-2018. Highest evapotranspiration rates are, according to the model, in the pre-monsoon season and in the southern are of the catchment, where agriculture, forest and shrubs are the main land cover types. Spatial variance exists within the winter season as well, but at a much smaller order of magnitude compared to the other seasons.

Total annual precipitation from four of the catchment's stations show spatial variation within the basin (Figure 10), with the wettest station being the mid-elevation Khudi Bazaar. Over the studied 20 year-period, total precipitation is decreasing at three out of the four stations where climate indices were analyzed, statistically significant with 26.1 mm/year at the lowest located station Rainastar.

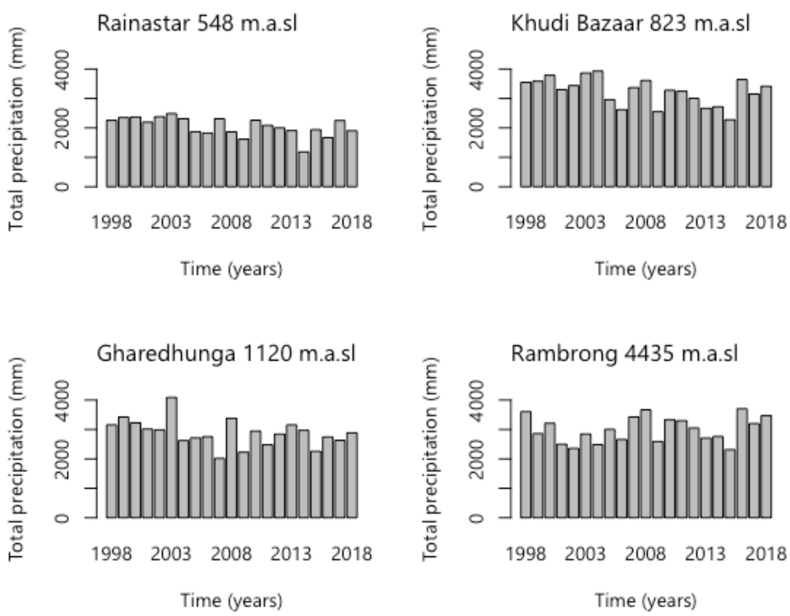

Figure 15. Total precipitation recordings from four of the catchment's stations, ranging in elevation from Rainastar at 548 m.a.s.l to Rambrong at 4435 m.a.s.l. Based on data from Department of Meteorology and Hydrology, Nepal (2019).

5.2 Trends in water dynamics 1998-2018

The outcome of the analysis of climate indices indicates that periods with consistent rainfall during several days are shortened, that there has been a decrease in days with heavy precipitation and an increasing trend in rainfall intensity.

Periods of consecutive wet days are slightly decreasing, and three out of four stations have a statistically significant increase in consecutive dry days with an increase of 2.13 to 4.92 days/year (Table 7). The annual count of days with rainfall exceeding 20 mm are slightly decreasing at a rate of 0.29-0.57 days/year at all stations except the highest located Rambrong.

Table 6. Summary of precipitation indices of total precipitation (PRCPTOT), days with rain exceeding 20 mm (R20mm), consecutive dry days (CDD), consecutive wet days (CWD) and simple daily intensity index (SDII) for stations Rainastar, Khudi Bazaar, Gharedhunga and Rambrong, ranging from 548 m.a.s.l to 4435 m.a.s.l. Significant trends are noted by *, shown in relation to the trend's Sen's slope estimator $Q_{Sen's}$.

Index	*Test*	*Rainastar, 548 m*	*Khudi Bazaar, 823 m*	*Gharedhunga, 1120 m*	*Rambrong, 4435 m*
PRCPTOT	$Q_{Sen's}$	-26.1*	-29.9	-27.8	15.6
	p-value	*0.023*	*0.057*	*0.057*	*0.49*
R20mm	$Q_{Sen's}$	-0.500*	-0.570*	-0.290	0.350
	p-value	*0.0098*	*0.023*	*0.38*	*0.18*
CDD	$Q_{Sen's}$	4.92*	1.60	3.47*	2.13*
	p-value	*0.0017*	*0.14*	*0.037*	*0.01*
CWD	$Q_{Sen's}$	-1.60*	-0.110	-0.340	-1.40
	p-value	*0.00063*	*0.86*	*0.051*	*0.07*
SDII	$Q_{Sen's}$	0.390	0.390	0.250*	0.450*
	p-value	*0.075*	*0.075*	*0.017*	*0.014*

The simple daily intensity index, SDII, which indicates the average amount of precipitation in wet days, increased at all four stations with between 0.25 and 0.45/mm/wet day, statistically significant at two out of four stations (Figure 14).

The index of maximum precipitation that fell within a five-day period (RX5DAY) in the monsoon season, show slight decreasing trends at rates of -4.5 to -12.7 mm/five-day period for all stations except the highest located Rambrong. The trend is statistically significant at Khudi Bazaar and Gharedhunga stations (*p-value* > *0.05*).

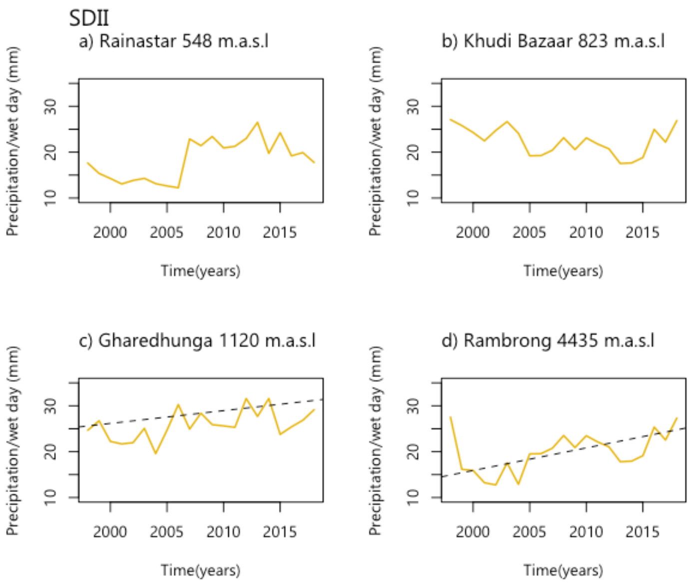

Figure 16. Simple daily intensity index for Rainastar, Khudi Bazaar, Gharedhunga and Rambrong (yellow line) shows statistically significant (*p-value* < *0.05)* positive trends at Gharedhunga and Rambrong (dashed lined).

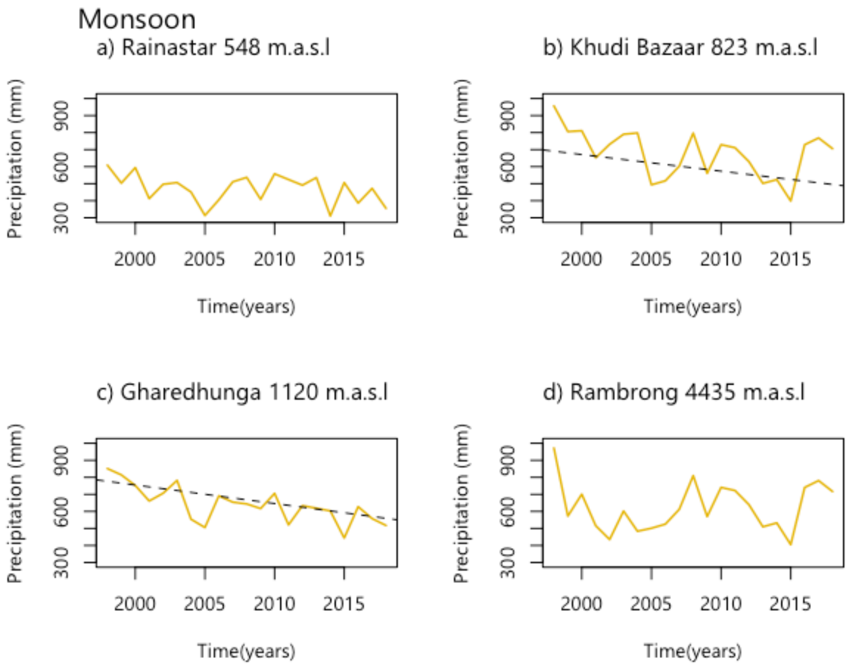

Figure 17. Monthly maximum 5-day precipitation for monsoon season at the four stations where climate indices are calculated (yellow line). A statistically significant negative trend in maximum amount of rain coming during a five-day period has occurred over the study period at Khudi Bazaar and Gharedhunga stations (dashed line).

Simultaneously as the results indicate increased rainfall intensity over the study period, there are positive trends in periods of dry days (CDD; Table 7) and an increase in warm days/year. Khudi Bazaar, the only station with a record of daily temperature observations for the whole study period, has an increasing rate of days with temperature above 25°C with 2 days/year (*p-value = 0.0019*; Figure 18). Maximum daily temperatures have increased at a rate of around 0.06°C/year (Table 8). A summary of the results of water dynamics and trend detection is seen in Table 8.

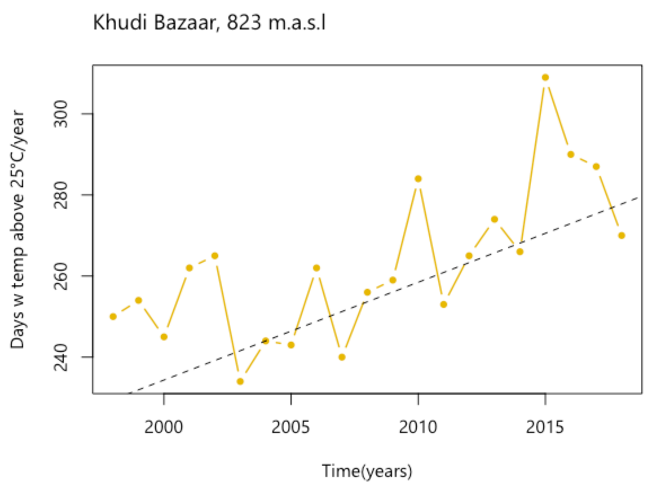

Figure 18. The trend of days per year with temperatures above 25°C, is increasing at Khudi Bazaar at a rate of 1.97 days/year over the period 1998-2018, with a p-value <0.05. Data from Department of Meteorology and Hydrology (2019).

Table 7. Results showing statistically significant positive trends in maximum temperature. Seasonal Mann Kendall was used for testing for monotonic trends, the non-parametric alternative for linear regression , and Sen's slope estimates the strength of the trend within the range of -1 to 1. Khudi Bazaar (in bold) is the only station with recorded temperature series for the whole study period. Stations in italic are purely based on lapse-rate estimated temperature series, while the rest of the stations belonging to the Annapurna network have observed temperature series for 3-5 years (1999-2004), thereafter temperatures estimated according to lapse rate.

Station	*p-value*	*Sen's slope*
Danfedana	$4.45*10^{-11}$	0.085
Faleni	*$5.91*10^{-9}$*	*0.063*
Gharedhunga	*$7.65*10^{-9}$*	*0.061*
Khudi Bazaar	**$7.60*10^{-9}$**	**0.062**
Kunchha	*$7.21*10^{-9}$*	*0.062*
Paiyu Khola	$8.11*10^{-9}$	0.062
Pasqam Village	$7.99*10^{-9}$	0.060
Rainastar	*$1.23*10^{-8}$*	*0.063*
Rambrong	$1.13*10^{-9}$	0.062
Syange	$6.24*10^{-9}$	0.061
Tamang	$4.05*10^{-9}$	0.060
Telbrung	$3.44*10^{-9}$	0.060

Table 8. Summary of outcomes from statistical analysis of ETCCDI climate indices and RHESSys modeling, showing identified water dynamics in Marsyandi river basin year 1998-2018, as well as changes in these spatiotemporal water dynamics

Water dynamics in Marsyandi river catchment, 1998-2018	**Identified trends in spatiotemporal water dynamics**
Monsoonal precipitation dominates water dynamics	Shortened coherent periods of rainfall
Average annual peak in discharge is seen in monsoon season, most often in August	Positive trend in rainfall intensity
Evapotranspiration rates peak in pre-monsoon season	Negative trend in days with heavy precipitation
	Negative trend in maximum precipitation during a five-day period in monsoon season

5.3 Local perceptions of water dynamics

The household surveys and focus group discussion served to see perceptions of change in water availability and causes of change. In the following section, statistical results of the household surveys are presented, followed by the analyzed outcomes from interviews and the focus group discussion.

Figure 19. Water tap in Gaunshahar, *image*: Hanna Ekström

5.3.1 Water dynamics in Gaunshahar

Participating households range from having two to 13 members. Agriculture or support from family members are the main sources of income, often a husband or son working as army soldiers, police officer or government officer in a larger urban center or another district in Nepal or India. The third main source of income is business within Gaunshahar, being a shop, local liquor production or a guest house.

Drinking water in Gaunshahar is mainly coming from a pipe system (Figure 19) connected to two different springs: Kaulipani and Tindari. The pipe system is financed by all households, through a common water committee. A small river creek (5-10 cm deep, 0.5-1 m wide, 15th of June 2019) through the village also provides water used for washing and for the animals and some participants get water from the local school.

No difference is seen between households when it comes to the activities that water is used for. All participants (n=54) say that water is used for drinking, cooking and washing, but not for irrigation of the fields which are all rain-fed. The majority (85 %) answered that they have enough water for domestic use (Figure 20).

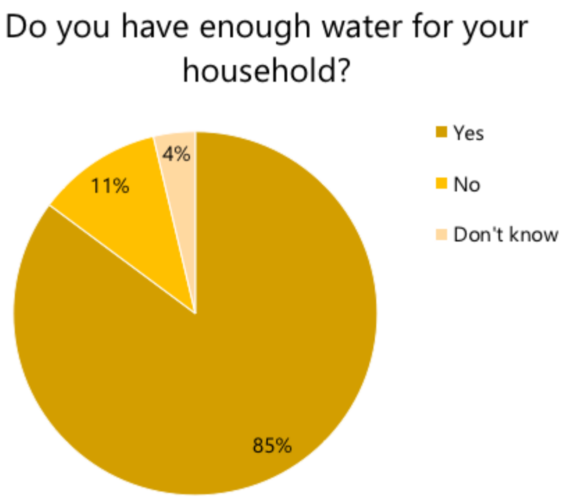

Figure 20. Participator's experiences of water sufficiency for domestic water use. Result from household surveys in Gaunshahar, June 2019. Total number of households, n= 54.

A smaller proportion of the participants, 18.5%, have suffered from bad water quality, but by some commented as not being an issue anymore: "Maybe 30 years ago, when it came from the rain water" (Man, 72). Another respondent means that still today, days of heavy rain sometimes causes bad water quality when sediment is flushed out into the pipe system.

Heavy rains are coupled to the monsoon season, a topic where the majority (48%, n=54) do not know if there has been changes, but according to 39 % of the participants, changes have occurred (Figure 21). Out of the portion answering that there has been changes, half of the answers indicate a later onset of the rain season. The other experience is that there is less rain coming in the rain season, and seven out of 21 just say that there has been changes, without specifying a reason.

The majority mentions no difficulties in getting water. Among the people experiencing times of the year when it is more difficult to get water, the two most common answers are less rain and a lot of people sharing the same tap. Being several households on one pipe is more common in the lower part of the village, where a higher proportion of people in the lower caste is living. "Society is big, we only have one tap"(Woman, 51). Further, it is mentioned that a small volume of water coming from the tap also means longer time spent to get enough water. "We used to have a shared tap for 7-8 houses, and some houses had a tank. With so many people sharing the same tap for drinking, washing, cooking, animals, it was hard to get it to last"(W,45). A man that has been working on installing the new pipe system, mentions that drying out of spring is the main reason for periods when it is difficult to get water (M,50). Other identified drivers of variation in water availability are changes in river flow, disturbance in the pipe system and dirty water (Figure 22).

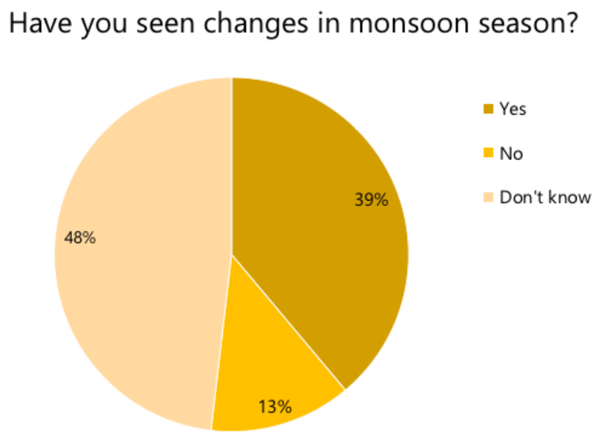

Figure 21. Proportion of participants that have seen changes in the monsoon season in the last 10 years. Results from household survey, Gaunshahar, June 2019 (n=54).

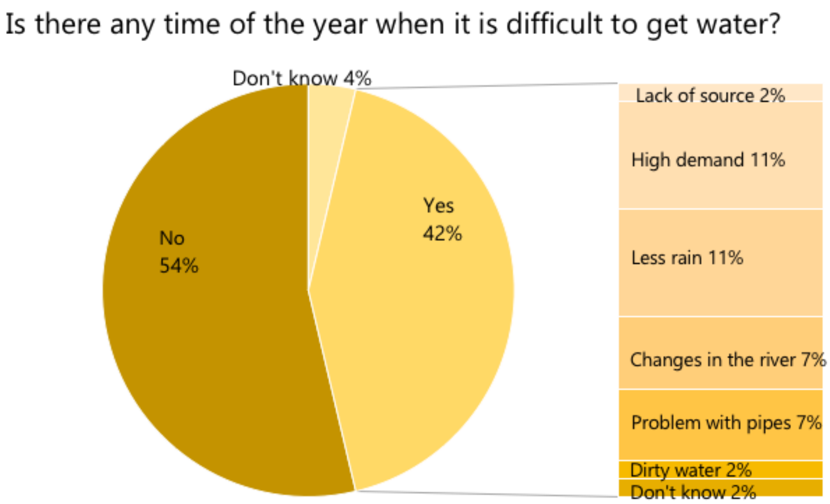

Figure 22. Difficulties in water availability and mentioned causes to lack of water, with total number of participating households being 54. Results from household survey in Gaunshahar, June 2019.

5.3.2 Perceptions of changes and of drivers of changes

The most common answer related to changes in water availability was related to the two-month-old pipe system. The following section shows more in-depth descriptions of what participants recognized as changes affecting water availability.

From a man living close to a water collecting tank, a pipe system is not a recent change: "We have had pipe system for a long time, before the earthquake. We also have a reserve system, the water tank for rain (...) But that is like a plan C, often there is water" (M, 37). Others have recently been connected and experience an improvement of water availability compared to before: "It used to be the hardest time in April, before we got the new pipe system" (W,70).

Even with the new pipe system, community members have experienced problems, when the pipe is broken or when someone further up the road is using and thereby disconnecting the pipe (Table 10)."We have to connect [the pipes] three times a day, because people disconnect all the time, you see?" (M, 37). A woman living upstream one of the water-collecting tanks addressed the location of one's house as a factor affecting the water accessibility. "My house is very high up, so we don't have collection of water like they have further down" (W,34). Located above the collecting tank, she could not use that water and her house plus five other houses in the surrounding area use to connect their pipes to the neighboring high school, without paying for the water.

Water for the household activities such as washing, cooking and drinking comes from the same source. Dirty water is thus a problem of water availability as much as the volume of water. Causes for dirty water are given as heavy rain events and dirty tank. Apart from heavy rains, the rain season is tightly connected to the agricultural yield. Community members describes how the rice fields usually are ready to harvest by the end of June. "Before, the rice had grown by now, you could cut it. But now, no…" (W, 31). A summary of identified causes of change can be seen in Figure 23.

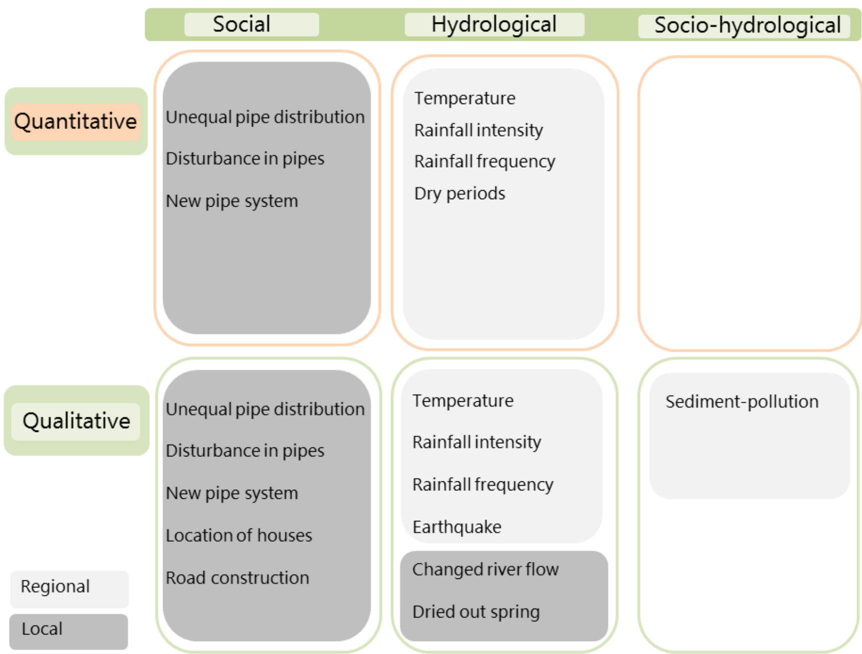

Figure 23. Summary of the results from quantitative statistical analysis of climate indices, hydro-ecological modelling and qualitative analysis of focus group discussions. The identified causes to changes are e.g. temperature, rainfall intensity and rainfall frequency on regional scale and unequal pipe distribution, drying up of spring and disturbance in the pipe system on local scale.

6.Discussion

The aim of this thesis has been to examine spatiotemporal water dynamics and how drivers of changes of these dynamics are perceived by people in a mid-hill mountain community. The results show that the dominantly rain-fed Marsyandi river basin has seasonal and interannual variations in precipitation and discharge patterns. Rainfall intensity has increased over the study period, while at the same time positive trends are seen in dry periods and maximum temperature. Of participants in Gaunshahar, 39% have observed changes in the monsoon season, with experiences highlighting both changes in precipitation volume, and a shift in the onset of the monsoon season. In the coming section the results are discussed in relation to each research question, elaborating on possible explanations based on the mixed-methods approach and finally reflections on the limitations of the study are given.

6.1 Water dynamics strongly influenced by rainfall patterns

Annual patterns of discharge show a peak in the monsoon season, but with high variation between years which the RHESSys model poorly described. The observed annual hydrographs for Marsyandi basin go in line with the discharge patterns that Kayastha et al. (2020) found for the catchment in year 2004-2010. Their analysis further found that baseflow contributes to a smaller proportion of the total streamflow of Marsyandi river, which could explain the high yearly variations in the catchment being due to variation in precipitation but also snow and ice-melt of a specific year (Kayastha et al. 2019). Such variations could apart from variations in the Indian monsoon be driven by variation in temperatures, but a catchment's response to different temperatures has in turn been seen to highly vary depending on the main driver of a basin's hydrology (Singh and Bengtsson 2005). For rain- and snow-fed catchments, increased temperature rates were shown to be followed by a linear increase in evaporation rates (Singh and Bengtsson 2005). For a complex catchment like Marsyandi river basin, mainly rain-fed but with contributions from snow and glacial melt as well, the rate of evaporation increase was explained to be higher than in simply rain-fed watersheds, but lower than in snow-fed basins. Different processes may counterbalance each other, e.g. a decrease in seasonal snow melt could be compensated by an increase in the rate of glacial melt (Singh and Bengtsson 2005). This could explain why, during the study period, no monotonic trend in discharge rates are seen, although a positive temperature trend and negative trend in total precipitation are observed. If the model's ability to capture variations between years were improved, the possible relationship between the positive trend in temperature and evapotranspiration rates could be an interesting topic for further studies of the basin.

Despite the uncertainties of describing inter-annual variation, the modeled evapotranspiration confirms the average yearly pattern shown by Larason Lambert and Chitrakar (1989), where they link the peak of evapotranspiration in pre-monsoon to the yearly pattern of solar radiation. As it becomes warmer and drier in combination with a peak of the topographically caused anabatic winds, which blows upward the mountain slopes, the atmosphere's ability to absorb water is at highest and so is the evapotranspiration in April-May. This pattern is typical for the mountain areas, according to Larason Lambert and Chitrakar (1989), as vapor pressure at higher elevations is reached earlier compared to lowlands. For future climate scenarios, higher elevations also showed a larger relative change in PET rates compared to lower elevations, seen in the neighboring Kaligandaki basin

(Bajracharya et al. 2018). In the current study, trends in evapotranspiration rates were not possible to examine. For a future study however, the relation between trends in evapotranspiration rates, elevation and temperature could be important for assessing future water dynamic change within the basin.

6.2 Shorter periods of consistent rain but higher rainfall intensity

The identified decrease in consecutive dry days was similarly found in a study of the neighboring Kali Gandaki river basin, based on 27 years of hydro-climatic data (Manandhar et al. 2012). The increasing trend of consecutive dry days is linked to a decreasing trend in monsoon rainfall. On a national level, an increase in consecutive dry days has in fact been seen across all elevations and latitudes, indicating an extension of the dry spell within the whole country (Baidya et al. 2008; Karki et al. 2017).

Simultaneously as extended dry periods, rainfall intensity show positive trends when looking at the simple daily intensity index. In contrast to SDII however, are the negative trends in RX5DAY over the monsoon season. As an indicator of major floods, a negative trend would indicate a decrease in floods during the monsoon season which in turn is coupled to landslides and inundation events(Turco and Llasat Botija 2011). A decrease in floods or landslide frequency has however not been noted in recent studies over Marsyandi river basin or other areas in central Nepal (Petley et al. 2007) It is therefore more likely to conclude that the negative trends in RX5DAY, the amount of rainfall during a five-day consecutive period, are despite being statistically significant, too small to have an effect on the frequency of major floods and landslides.

A result that on the other hand has firm support in current research is the increase in maximum temperature and the increase in days with temperature above 25° C. The magnitude of increasing maximum temperature by 0.06°C/year is higher than the 0.04°C/year that was reported by Poudel et al (2020) for the whole Nepalese Himalayas but follows the general pattern of increasing temperatures over the last decades seen in earlier research on both national levels, with amplified affects in mountain areas (Baidya et al. 2008) and in the larger region of central Himalayas (Poudel et al. 2020; Shrestha et al. 1999). The clearer patterns seen in temperature compared to precipitation are not surprising, as temperature changes have been shown to be more consistent than precipitation changes in studies of climate change (Barnett et al. 2005). More days with warmer temperatures as well as longer dry spells points toward both warmer and drier future scenarios.

The days when it actually rains have increased in rainfall intensity, in line with earlier research from Marsyandi basin (Parajuli et al. 2015). The variation is not uniform over the whole central Himalayan region however, as rainfall intensity in the neighboring catchment Kali Gandaki River Basin was reported to decrease at the majority of stations (Manandhar et al. 2012). For Nepal as a whole, Baidya et al., (2008) demonstrate complexity in precipitation patterns but conclude a general increase in total and extreme precipitation. Contradictory to the national trend, Marsyandi river basin has a slight decrease in days with heavy precipitation (R20), whereas 62% of the considered stations on national level recorded an increasing trend between 1961-2006 (Baidya et al. 2008). Drivers to the changes in precipitation intensity and extreme rainfall events are identified as being changes in the Indian monsoon, which in turn is coupled to larger climatic oscillations such as the El Niño Southern Oscillation (Bohlinger and Sorteberg 2018).

6.3 The importance of a new pipe system

Through causation coding and the socio-hydrological tool of social/hydrological subsystems, perceptions about water dynamics and potential drivers to changes in water availability have been analyzed. The following section develops three main topics revealed from the analysis: an interesting contradiction in the answers linked to water availability, the importance of the new pipe system and a tendency to focus on single events rather than long term trends.

In relation to the first research question, the way in which participants talk about fluctuations in water dynamics is mainly concerning how water availability varies during the course of a year rather than between years. The majority of participants answer that they have enough available water for domestic use but points out a later harvest of rice in year 2019, which some farmers think is due to a later start of the rain season and others recognize as being caused by a smaller volume of rain during the monsoon season. As agricultural fields are explained to be mainly rain-fed, there was however no conflict identified between water use for domestic versus agricultural use. The opposite experiences were noted in a case study in two catchments east of Kathmandu, where farmers expressed a concern about an increasing water shortage as precipitation amounts were decreasing in recent years, while agricultural practice had gone more toward cash crops that required more regular irrigation (Merz et al. 2003). A similar development toward increased use of cash crops and agricultural intensification was not noted in Gaunshahar, which could explain why there was no signs of conflict between water for irrigation and household consumption. It could however be an important topic to keep track of for future studies.

The most commonly mentioned cause of changes in water dynamics in Gaunshahar is the new pipe system, which provides a new infrastructure of water to a majority of the participants' households. Several respondents mention an improvement of water availability, both in quantity, quality and the time it takes to get water, after installation of the new pipe system. In this sense, the pipe system could be interpreted as the most dominant recent change for Gaunshahar's water availability, and in turn a change that works as a buffer for other changes, as it increases the security of water availability in months when lack of water usually is a problem. Especially so, as respondents often mention only one source of water, which means that the dependency on that one source of water is high. Mao et al. (2017) discusses how the concept of socio-hydrology can support an understanding of a systems resilience to changes, with resilience being a system's capacity of meeting disturbances without large changes in the nature or function of the system (Walker et al. 2004). By constructing water collecting tanks and a closed pipe infrastructure, the village has become more resilient to changes in water supply, comparable to what was discussed by participants in earlier studies in Nepalese mid- and high-hills (Merrey et al. 2018; Poudel and Duex 2017). In this sense, the new pipe system as a change in the social sub-system has increased the resilience to changing water dynamics within the socio-hydrological system in total.

There are however still problems related to the pipe system as it is working with varying effectiveness in different parts of the village. Participants mention that the distribution of household's per pipe is not equal throughout the village and hierarchical structures within the village organization makes it easier for some households than other to get water. When some answer that they have been sharing one tap for 7-8 households, but another participant mention having a plan C in case of water disturbance, the results point toward an unequal distribution of the water system. This shows that despite sufficient water supply, water availability also has a social aspect, a social accessibility to water (Biggs et al. 2013a). Different possibilities to water access, both in time and volume, can put higher pressure on already pressured families (Ensor et al. 2019) and as shown by an earlier study in Lamjung district, adaptation to climate change can also strengthen existing power relations (Gentle et al. 2018). The tendency to social structures affecting water access is a theme that would need a deeper analysis in future studies, for example by using methods that account for different socio-economic groups within the village.

Participants discussed changes in seasonality in relation to the crop yields of the current year, but apart from this, answers seldom reflect concerns about long-term effects of climate or weather as a threat to agricultural or domestic water use. As an example, heavy rains every now and then are mentioned as affecting the water quality due to sediment flushed out into the system, but no answers reflect over long term trends in frequency of heavy rainfall. Another example are temperatures where increasing long term trends of maximum temperatures are seen in the quantitative data, but hot weather mentioned more as being of single event character in the interviews. This could be interpreted as in the local reality, actions are only taken to short term extreme events and answers are therefore focused on aspects that are possible to change (Merz et al. 2003). Similar reflections were made within a study in the regions of Chitwan and Kaski, located to the south and east of Marsyandi river basin (Ensor et al. 2019). Rarely did the study's respondents mention climate or weather events as challenges for their livelihoods, and only when directly asked about climate change participants answered that the rain did not come as expected a certain year (Ensor et al. 2019). At the same time, communities in Nepal have a long history of adapting to a challenging climate, and several studies have shown wide awareness of climate change within Himalayan communities. The practical adaptation actions and the focus of the answers may thus rather be understood as being due to a combination of factors, where economy plays a big role, rather than merely a response to a long-term climate change (Biggs et al. 2013b; Berrang-Ford et al. 2011; Ensor et al. 2019).

6.4 Strong dependence on seasonal rainfall

Whereas few of the participants mentioned long term trends of changes in their answers, trends of changes in water dynamics have been detected in the study period through the use of climate indices and modelling. A first important remark is that no disagreements between results from the different methods used were found. The different methods indicate different trends with varying strength however, and some explanations are found in the interviews that are not found in the scales of statistical and modelling analysis. The following section concludes around common themes in the different methodologies used, results on different scales and the variance of aspects that were seen by using mixed-methods approach.

The way in which participants in Gaunshahar put emphasis on the importance of rainfall for agricultural yield, show a strong dependence on seasonal rainfall. But as the statistical analysis and modelling results suggest, increasing trends of continuous dry periods and more intense precipitation extremes are shown in the last 20 years. If the trends of more unpredicted precipitation extremes are to continue, as studies suggest (Parajuli et al. 2015; Wester et al. 2019) precipitation could in fact be seen as the main biophysical driver of vulnerability for communities in Marsyandi river basin, and not glacial melt as the situation of climate change in Himalayas is often being portrayed (McDowell et al. 2013).

There are cases where the results from one method are not visible in another, a result that contradicts that local knowledge can be used when meteorological data is lacking, as proposed by Joshi et al. (2019). Here, the different methods rather reveal aspects of changed water dynamics on different scales. As Konchar et al. (2015) discusses in their study over the Annapurna area, socio-cultural traditions and local ecological knowledge affect the participants' view and their answers thus highlight other aspects than those seen on regional or global scale. The drivers of changes identified through the quantitative methods coincide with six of the drivers identified through the qualitative focus group discussions, but they differ in the number of drivers identified on regional and local scale respectively. In some case, it is possible to draw a link from the regional scale identified in the quantitative section to what was identified on local scale, e.g. climate trends identify dry periods, and participants mentioned drying out of spring as one cause. The trends in climate indices and regional modelling give thus a larger context that is not given through the interviews. Manandhar et al (2012) noted similar patterns when using a combination of hydro-climatic indices and perception interviews. By using a mixed-methods approach, a more enriched result with aspects from local to basin-wide scale has been revealed. Such conclusions are important in the larger perspective of securing water supply for future needs in the whole Hindu-Kush Himalaya region. In the yearly assessment report from the International Center for Integrated Mountain Development, ICIMOD, it is stated that water availability alone is not enough if not supported by good governance. Such governance includes trade-offs between upstream and downstream, rural and urban, water needs and use. Results that take local, basin-wide and national scales in consideration are therefore crucial for future water supply in the Himalayas (Wester et al. 2019).

6.5 Limitations and future studies

Limitations include sampling of ground control points, adjustment of model parameters as well as sampling technique for the household surveys, starting with a note about land use changes. The extensiveness of the results is limited by the fact that land use in the current model application is a constant variable over time, i.e. a single land use map based on satellite imagery from year 1999 is used as base for the whole study period. Ongoing land use changes have however been noted, in the lower part of the catchment as increasing coverage of forest and agricultural land at the expense of shrubland as well as changed access to agricultural land after the earthquake, according to earlier research (Shrestha 2014; Ghoka 2015). A LULC change analysis and its possible effects on water availability in proportion to the effects of climate change was out of the scope of the current study but remains an interesting topic for future research.

Regarding the model outcome, the parameterization process was limited within the scope of this thesis, but RHESSys provides a large range of parameters that could be adjusted. For future studies, possibilities for improvement would be to tune the vegetation function parameters, e.g. field measured Leaf Area Index, a factor that presumably has an effect on the absolute values of evapotranspiration being modeled. Another factor shown to affect the modeled evapotranspiration is the resolution of the DSM (Duffy and Yu 2018), which in this case was limited to 30 m. Secondly, parameters controlling glacial and snow dynamics could be tuned to the area. Snow cover is modelled based on temperature, i.e. an area with constant temperatures below zero would be a permanently snow-covered area, but parameters controlling melt would be possible to adjust. A sensitivity analysis of the different snow controlling parameters as well as the effect of different homogenizations processes of the climate data could therefore be suggestions for future studies.

Thirdly, field work was done in the beginning of the monsoon season which made it difficult to visit the whole basin area due to risk of landslides. This had implications on the collection of ground truth points for land use classification, which had to be done based on high resolution satellite imagery. The method has proven to be efficient in studies which lack sampled ground control data, but still a possible source of error for the final land use classification compared to sampling of ground truth points.

Lack of metadata has in some cases limited the possibilities for quality check. For temperature trends, only Khudi Bazaar station had series of temperature recordings over the whole study period, which means that possible errors in the series are affecting the rest of the stations. For soil texture, lack of metadata or comparable data sets meant that possible errors were not possible to detect before analysis.

Finally, the generalizability of the results was limited by the sampling technique of participants in the village, where a stratified random sampling of predetermined groups in the village structure as well as more focus group discussions would have enhanced generalizability. From the participants answers, there are indications of variance in the perceptions depending on location of the household and caste, but as the participants were treated as one group no larger conclusions about differences within the village can be drawn from the survey results. Moreover, variance in answers were noted from different translators, which infers that the communication with each translator around expectations and purpose of the different questions could have been clearer.

Conclusions

The aim of this thesis has been to identify water dynamics over space and time in Marsyandi river basin, possible trends in these water dynamics over the study period 1998 to 2018 as well as how they are perceived locally in a village at the mid-hills, Gaunshahar. To conclude, water dynamics in Marsyandi river basin are dominated by rainfall patterns, showing a strong seasonal variation in discharge with peak in August whereas evapotranspiration peaks in May. Over the study period, 1998-2018, consecutive dry days increase by 2-5 days/year and days with temperatures above 25° C increase with 2 days/year while at the same time a negative trend is noted in total precipitation, with -26.1 mm/year. A majority of the households in Gaunshahar have enough water for their domestic needs and express that a new pipe system has been the main recent driver of change in water availability. The system has made it easier to get enough water for household consumption, but households further away from the water collecting tanks mention that they still have difficulties every now and then. Overall, participants have a strong reliance on rainfall for agricultural yield, and availability of spring water for drinking water access. The combined outcomes from statistical analysis of climate indices, hydro-ecological modelling, surveys and focus group discussions highlights changes in precipitation patterns as the main biophysical driver to changes in water dynamics. RHESSys show promising results for application in a Himalayan catchment but site-specific adjustments of the model's parameters are needed. After such adjustments, interesting topics for future studies include: incorporation of land use changes and possible relationship between temperature trends and evapotranspiration rates. Moreover, a deeper look into the causes of different perceptions about water availability would be an important topic for future research, in order to understand climate change and its effects on water availability in the mid-hills of Nepal.

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SI: Statistical tests

A summary of statistical tests used in the thesis with general description and motivation for use in the current study.

Test	*Area of usage*	*Description*	*Motivation for use in current study*
Q-Q plots	Initial quality control of climatological data: climate series tested against normal distribution	Compare the quantiles of two data sets, one being recorded values and the other a standard normal distribution. If values fall on a straight line, the slope's equal to the st. dev and intercept corresponds to the mean of the values, the data set resemble a normal distribution (Lee et al. 1998).	- Graphical, simple yet efficient method - Proven to show adequate results for climate series analysis(Singh and Qin 2019)
SNHT	Homogenization of climate series	The Standard Normal Homogeneity Test is computed on composite reference series. H_0 = the data are normally distributed, independent and random quantities. H_A = the presence of a step-like break in homogeneity (Alexandersson 1986; Costa and Soares 2009)	- Makes it possible to take advantage of all data possible - Commonly used and therefore easy to compare to other studies
Cohen's kappa	Evaluation of land use classification	Cohen's kappa value is the difference in agreement of observed vs mapped land use, and the result given by chance(Rogerson 2014)	- A quick overview of accuracy - Used in earlier research of the study area, easy to compare (Shrestha 2007)
User's & producer's accuracy	Evaluation of land use classification	User's and producer's accuracy give separate accuracy estimates of a pixel in comparison to reality (user's accuracy) and how well a point in reality is being correctly classified on the map (producer's accuracy)(Rogerson 2014)	- A more detailed view of the accuracy than Cohen's kappa or overall accuracy
Mann-Kendall	Trend testing of non-normally distributed data	The non-parametric test detects monotonically increasing or decreasing trends with the assumption that the data is without seasonal dependence or auto-correlation (Mann 1945; Kendall 1948)	- Widely used in hydrological time series analysis
Seasonal Mann-Kendall	Trend testing of climate series where seasonal dependence is expected:	A version of the Mann-Kendall trend test where each season is analyzed separately (Hirsch et al. 1982)	-To account for seasonal variation in the climate series
Block-bootstrapped Mann- Kendall	Trend testing in climate series where the block-bootstrap technique reduce autocorrelation	To account for autocorrelation before performing a Mann-Kendall trend test. The data are shuffled several times and the test statistic is calculated on each new version of the data set. The distribution of all trend statistics can be compared to the original data (Önöz and Bayazit 2012)	- Powerful trend detection after eliminating the effect of autocorrelation -Shown to have less risk of over- or underestimates of trends compared to similar preprocessing techniques (Villafuerte et al. 2014)
Theil Sen's slope	Estimating magnitude of a non-parametric trend	Fits a line to the data points by using the median value of all slopes from pairwise lines within the data set (Sen 1968; Poudel et al. 2020)	- A robust alternative for non-parametric data to examine the magnitude of a trend

SII: Survey and focus group discussion forms

Question forms for focus group discussion and household surveys held in Gaunshahar, June 2019.

Focus group: Gaunshahar July 2019

Number of participants:
Female:
Male:

Availability

Where do you get water from? How? Do you have to pay?

Have you noticed any changes in water availability?

Quality

How is the water quality?

Season

Is there any time of the year when it is difficult to get water?

Has there been changes in the rain season?

Water use

Do you use irrigation?

Why is it hard to get water?

Drivers

Do you have any relation to hydropower?

When there is less water available, what do you think is the reason for that?

Survey, Gaunshahar June-July 2019

1. Female/Male	Female ☐ Male ☐
2. Age	
3. How many persons live in your house?	
4. What is the main source of income for your family?	☐ Agriculture ☐ Business in Gaunshahar ☐ Business outside Gaunshahar ☐ Other:__________
5. For how long have you lived in Gaunshahar?	
6. What do you use water for in your family?	
7. How do you get drinking water?	
8. Where do you get water for washing and cooking?	
9. Have you or members in your household suffered from bas water quality in your local area?	☐ Yes ☐ No
10. Is the water available enough for what you use in your house?	☐ Yes ☐ No
11. a) Is there a time of the year when it is difficult to get water?	☐ Yes ☐ No
11. b) If yes, why is it difficult?	☐ Drying out of spring ☐ Less rain ☐ Changes in the river ☐ Many people ☐ Increased business ☐ Other
12. Have there been any changes in the monsoon season?	