

# Methods to Investigate the Hydrology of the Himalayan Springs: A Review



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**Methods to Investigate the Hydrology of the Himalayan  
Springs: A Review**

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## Summary

Springs are the major source of freshwater in many small mountainous watersheds within the Himalayan region. In recent years, their flow rates have diminished, but the reasons for this are not self-evident. This paper reviews the methods that investigate the hydrology of springs, with a focus on the Himalayan region. The methods are classified as field-based empirical and desk-based analytical. Field-based empirical methods help to characterize geology, hydrology, climate and land-use patterns. Desk-based analytical methods guide quantification of fluxes and responses across watersheds, which are potential inputs to the development of hydrogeological maps, quantification of water balances, conceptualization of processes that control or influence the movement and storage of groundwater, and development of a mathematical model, which may guide further sustainable development of water resources. The review identified that there are a few detailed studies in the Indian Himalayas, but studies in Nepal are very limited. Due to the paucity of literature from the Himalayas, the review includes literature from other parts of the world, which may guide research on springs in the Himalayas. The paper recommends analysis of existing grey and published literature, and data first prior to embarking on costly field investigations. The review reveals that chemical and isotope analyses – mostly water dating and stable isotope (e.g.,  $\delta^{18}\text{O}$ ) analyses – could be an appropriate entry point to commence field investigations, because of their potential to map complex spring pathways, including linkages between aquifers. This should be combined with the building of hydrogeological maps with the available data. Output from desktop analyses, field investigations and hydrogeological maps could then contribute to the establishment of a conceptual model, which could form the basis for a numerical model.



## **INTRODUCTION**

Springs are the major, if not the only, source of agricultural and domestic water for many rural communities in mountainous regions, such as the Himalayas (Bartarya 1991; Bartarya and Valdiya 1989; Negi and Joshi 2004; Pandit et al. 2007; Vashisht and Sharma 2007; NDF 2014). Natural stressors (especially climate change) and improper watershed management have led to a decrease in discharge in many Himalayan springs (Agarwal et al. 2012). For example, Valdiya and Bartarya (1989) reported a 40% reduction in spring discharge over a 35-year period (1951 to 1986) in the Kumaun Himalaya region, which was mostly attributed to changes in land-use patterns and vegetation. They identified that 75% of the springs have gone dry and the average stream discharge has declined by ~40%. In another study, Mahamuni and Kulkarni (2012) identified that nearly 8,000 villages were facing acute water shortages due to the drying up of springs in the Himalayan region. ICIMOD (2015) reported that, in the Nepali mid-hill region, a combination of biophysical (e.g., climate variability, changes in land use) and socioeconomic (e.g., spring maintenance) factors were responsible for the drying up of springs. Vashisht (2008) indicated that, if springs and small seepage canals are managed properly in the Siwalik foothill regions of the Himalayas, water scarcity could be averted.

Therefore, drying up of springs and water scarcity issues underscore the need to increase the understanding of spring hydrology, especially in the Himalayan region. In a review of micro-scale and meso-scale studies, Negi (2002) highlighted the need for systematic monitoring to aid the management of Himalayan springs. Bruijnzeel and Bremmer (1989) and Alford (1992) concluded that the current understanding of hydrological processes in the Himalayas is inadequate, and management plans stemming from inadequate understanding would not solve water scarcity challenges. Research targeted at understanding the functioning of springs is thus warranted.

In order to improve water availability for rural communities in the Himalayan regions, there had been numerous watershed interventions in the past. Most interventions were not site-specific and did not take into account karst geology and preferential pathways in aquifers (Agarwal et al. 2012). Instead, a 'one-size-fits-all' approach was adopted in most interventions (Sharma et al. 2000a, 2000b; Sharma and Shakya 2006). Furthermore, studies to assess the impacts and sustainability of these interventions are rare, especially to quantify their impact on spring discharge. As a result, the impact of these interventions on increasing spring discharge is limited.

Advances in knowledge of Himalayan springs is limited, due to inadequate investigations, and a lack of synthesis of existing information in published and grey literature. This review aims to fill this gap. The review identified that there are a few detailed studies in the Indian region of the Himalayas, but studies in the Nepal region are very limited. Due to the paucity of literature from the Himalayas, the review includes literature from other parts of the world, which may guide future research on springs in the Himalayas.

The review will begin with an explanation of the geology of the region and identification of the types of springs, followed by a review of the methods used to characterize spring hydrology. Then, the knowledge gaps to characterize Himalayan springs will be identified. This review concludes with recommendations to assist future research, especially for the Himalayan region.

## **HIMALAYAN REGION**

The Himalayan region extends approximately 2,400 km and runs northwest to southeast, with a width of 150 to 400 km (Hasnain 1999). The north and south are bordered by the Tibetan Plateau and the Indo-Gangetic Plains, while the west has the Karakoram and Hindu Kush ranges, and the

east has the Indian states of Assam and Arunachal Pradesh. The Himalayan range passes through five countries: India, Nepal, Bhutan, China (Tibet) and Pakistan.

The Himalayas were formed due to the tectonic uplift of sedimentary deposits (Gansser 1964; Le Fort 1975; Valdiya and Bartarya 1989; Hasnain 1999) and, as a result, is characterized by a high degree of fragility, and a natural tendency to weather and decompose due to climatic factors (Thakur 1993; Kumar and Rawat 1996; Dahal and Hasegawa 2008). Therefore, the geology of the Himalayan range is influenced by past effects of deeply eroded thrust, and the effects of current mechanisms of a working thrust (Le Fort 1975). Of the thrusts, those that characterize the structural framework of the Himalayas are: the Main Central Thrust (MCT), the Main Boundary Thrust (MBT) and the Main Frontal Thrust (MFT).

The Himalayas contain the largest amount of ice in the world after the Antarctica and Arctic polar regions. Approximately 15,000 glaciers are located in the Himalayas, with a net water storage of 1,012 m<sup>3</sup> (Puri 1994; Cruz et al. 2007). The meltwater from these ice systems leads to the formation of many rivers and streams. It must be noted that three major rivers of the world – the Indus, Ganges and the Brahmaputra – all originate in the Himalayas.

Within the Ganges River Basin, the Himalayan region is covered mostly by snow throughout the year, and its lithology consists mainly of crystalline, sedimentary and meta-sedimentary rocks. The Terai Bhabar belt region consists of boulder, cobble, pebble, gravels, sands, silt and clays, while the Siwalik region consists of sedimentary rocks often partly lithified. The Plains consist of unconsolidated alluvium and aeolian deposits (clays and silts, gravels and sands, lenses of peat and organic matter, carbonate and siliceous concretions [Kankar]), while the floodplain and delta region consists of grey medium to coarse sands capped by 10-60 m of surface clay, silty clay and peat (Jain et al. 2009).

## **CLASSIFICATION OF SPRINGS**

Types of springs may vary according to flow rates, seasonality of flows, water temperature, water quality and the presence of dissolved gases. Fetter (1994) classified springs into six dominant types based on their geology:

- Depression springs – Undulating topography intersects the water table to form depression springs.
- Contact springs – When permeable rocks or sediments overlie less permeable units, infiltrated water flows laterally (due to higher hydraulic conductivity) rather than vertically due to gravity. Thus, preferential flow paths are created at the contact of different geologic units with variable hydraulic conductivity. Water flowing through these flow paths emerges at the surface to form contact springs.
- Fault springs – When faults have higher hydraulic conductivity than the material in which they are embedded in due to stress, movement or weathering, the faults can act as a regional boundary for groundwater movement and provide a preferential flow path for water. When water moves along fault lines and discharges at the surface, fault springs are formed.
- Sinkhole or karst springs – Limestone bedrock can have large conduits, cavities and channels (termed karst), which act as preferential flow paths for groundwater. When water in these flow paths is under artesian pressure, sinkhole or karst springs are formed.

- Joint springs – Many joints with high hydraulic conductivity may be present in low permeability rocks. When water flows in these joints, joint springs are formed.
- Fracture springs – Because fractures have a higher hydraulic conductivity than adjoining rocks, water preferentially flows in these fractures, thus forming fractured springs.

In some cases, understanding the geology of mountainous regions using geophysical exploration is difficult due to a lack of access. Hence, Mahamuni and Kulkarni (2012) used seasonality and magnitude of spring discharge rates to categorize spring types in the Himalayan region. According to their classification, depression springs are those with a discharge less than 150 liters per minute (lpm); contact springs are those with a seasonal discharge (with no flow during dry periods) up to 120 lpm during the monsoon season; fracture springs have discharges similar to contact springs, but are perennial; and fault springs are those with discharge rates up to 30 lpm and are perennial. Results from the studies by Mahamuni and Kulkarni (2012) suggest that the Himalayan springs are mostly depression springs, formed due to undulation of the topography. In recent years, many methods have been used to investigate springs.

## **METHODS TO INVESTIGATE SPRING HYDROLOGY**

Field investigations are essential for understanding groundwater in karst systems (Fetter 1994; Taylor and Greene 2008). Spring discharge is influenced by spatial variation in topography and geology as well as temporal variation in hydrology and climate. Hence, researchers use a combination of empirical and analytical methods to understand spring discharge. In the following sections, the successful use of empirical and analytical methods to investigate spring hydrology is reviewed.

### **Empirical Methods**

Empirical methods, through direct and indirect observations, help researchers gain knowledge of spring hydrology. Direct measurements include monitoring spatial and temporal variations in groundwater levels and pump tests. Tracers are often used to characterize springs. In many situations, obtaining necessary empirical data can be challenging or impossible, because parts of the catchment may be inaccessible to researchers.

#### ***Pump Tests and Groundwater Monitoring***

Springs integrate flow in aquifers. Pump tests are point methods that quantify hydraulic attributes of aquifers that feed springs. According to Hickey (1984), a variable-rate pumping test can be used to develop flow nets for aquifers linked to springs. He showed that, by using variable pumping rates and monitoring drawdown, multiple flow paths could be identified. Kiraly (1975, 2002) indicated that a combination of core, packer, slug and pump tests was more effective to identify permeable fractures that provide flow paths. Continuous water level monitoring in areas with limited areal recharge can assist in identifying preferential flow paths within an aquifer (Worthington 2003).

#### ***Dyes as Tracers***

Spatial heterogeneity and anisotropy in geologic parameters require intensive field measurements or observations to understand spring hydrology. Establishing and maintaining field networks can become expensive and time consuming. On the other hand, analysis of water chemistry can provide

insights into the occurrence and interactions of water with aquifer materials, thereby providing insights into the residence time of groundwater (Jeelani et al. 2015). Storm-pulse tracing, another technique used to locate small springs, involves the injection of tracers into a sinkhole and recovery of dye tracers.

Jeelani et al. (2011) used water chemistry indices and physical properties (especially temperature, pH, total dissolved solids [TDS], nitrate and calcium) to estimate stream water sources and the dominant chemical processes, such as carbonate dissolution, silicate weathering and de-dolomitization. These indices indirectly provided data on the retention time of water in the aquifer. Their study also showed that the springwater freshening occurred due to water from streams, as in this case, streams were the source of springs. Therefore, stream management activities were more important to manage spring flow. In another study, Shivanna et al. (2008) used chemical analyses to identify recharge areas of springs in Uttarakhand, India. The chemistry of high altitude springs was similar to that of precipitation, indicating that precipitation was the major source of recharge and spring discharge in this area. By developing a relationship between altitude and water chemistry, recharge areas for springs were demarcated and recharge structures were installed. Chemical analysis of pre- and post-monsoon spring discharges indicated that watershed interventions, especially subsurface dikes, check bunds and contour trenches, maintained discharge during periods when springs were historically dry.

In some cases, water chemistry is analyzed while conducting dye tracer tests. Coward et al. (1972) used dye tracers to estimate flow paths of springs in the Kashmir Valley. Rhodamine B dye (tracer) was used along with charcoal (detectors). The study reported water travel times of 48 to 68 hours from source to discharge.

However, the success of dye tracing methods to understand spring hydrology has been limited. This is because the tracers were never detected in monitoring wells, when boreholes (in which the tracer was injected) did not intersect the flow lines. The costs for analyzing water chemistry and dye tracers are still high, and may not be affordable by small communities that depend on local springs. Many of the aforementioned studies indicate the sources of springwater qualitatively, but do not quantify the exact amount. Spatiotemporal variations are also not discussed, and hence the studies may have limited impact on preserving springwater sources. Furthermore, many governments restrict the use of chemical dyes due to environmental pollution concerns. Hence, the use of naturally occurring isotopes as spring discharge markers has become popular among researchers.

### ***Isotopes as Tracers***

The use of isotopes for hydrological research was introduced in the 1960s, mostly along with other methods, to understand recharge and residence times (Sklash 1990; Buttle 1994; Kendall and Caldwell 1998; McDonnell 2003; Vitvar et al. 2005; Kumar 2013). Vitvar et al. (2005) provided a review of the use of isotopes in hydrological research, and indicated that the use of isotopes has largely aided in the assessment of temporal variations of flow mechanisms and assessment of catchment hydrologic processes. They also feel that research on the relationship between baseflow residence time and basin area is limited, and urge future researchers to engage in multi-isotope studies rather than studies fixated on a single isotope. In addition, the review encourages future studies to be conducted in large-scale basins, after careful consideration of the relationship between groundwater and surface water mechanisms. Atoms in the natural water molecule –  $^{18}\text{O}$ ,  $^2\text{H}$  and  $^3\text{H}$  – have been identified as ideal water tracers. These isotopes are commonly used to determine the age and the source of groundwater (Davis et al. 1980; Gat and Gonfiantini 1981; Faure 1986;

Singh and France-Lanord 2002; Mazor 2003; Dickin 2005; Mook 2006; Rao 2006; Gat 2010; Kendall and McDonnell 2012).

Globally, many studies have used different isotopes for their research objective. In a study in the Yushugou River Basin, China, Wang et al. (2015) used  $\delta^{18}\text{O}$  to infer the percentage contributions of snowmelt (63%) and groundwater (springs 27%) to flooding of the Yushugou River. Such information on splitting the sources of floods is also critical in the Himalayan region, especially in the Koshi River Basin where annual floods are common (Chinnasamy et al. 2015). In another study in Iraq, Mustafa et al. (2015) studied the  $\delta^{18}\text{O}$  and  $\delta^2\text{H}$  composition in eight springs to distinguish spring origins, and identified three aquifers in the region: Behkme aquifer, Kometan aquifer and Shiranish aquifer, contributing to spring flow. With such inferences, aquifer properties can be assessed, leading to the development of site-specific management plans. Therefore, researchers in the Himalayan region should use multi-isotope analysis to understand contributions of different aquifers to spring flow.

In another study, Lambán et al. (2015) used  $\delta^{18}\text{O}$  and  $\delta^2\text{H}$  to delineate recharge areas for springs in the Ordesa and Monte Perdido National Park (Northern Spain). Vallejos et al. (2015) used  $\delta^{18}\text{O}$  to identify the recharge area for aquifers and springs in the karstic macro system of Sierra de Gador (Southeastern Spain). Katsuyama et al. (2015) studied the distribution of  $\delta^{18}\text{O}$  and  $\delta^2\text{H}$  in stream waters across the Japanese archipelago, encompassing 1,278 forests. Their study results produced iso-scapes (i.e., mapping spatiotemporal distributions of stable isotopes across macro-scale study areas) which were useful for identifying sources and recharge rates for the springs and streams.

Sánchez-Murillo et al. (2015) estimated the  $\delta^{18}\text{O}$  and  $\delta^2\text{H}$  isotope compositions in groundwater to estimate the mean transit times in natural and human-altered watersheds. Their results indicated that the forested regions retained water longer (low transit times) than the human-altered systems.

Jeelani et al. (2010) used  $\delta^{18}\text{O}$  tracers to identify recharge areas in the Liddar watershed, western Himalaya. Water samples were collected from six springs, 14 streams, and 8 precipitation sites for over a year (January 2008 to 2009). Streams and springs with depleted  $\delta^{18}\text{O}$  indicated recharge from snowmelt, while less isotopic depletion indicated baseflow and high  $\delta^{18}\text{O}$  indicated rainfall. The  $\delta^{18}\text{O}$  concentration decreased with increased temperature for rainfall samples, and was in agreement with other similar studies. The study concluded that the springs were mostly fed by rainfall. Temporal variations in isotopic composition indicated distinct periods of snowmelt and rainfall contributions, and hence less lag time. The  $\delta^{18}\text{O}$  concentrations of the springs and streams followed similar trends, indicating that they were hydrologically connected. The study concluded that  $\delta^{18}\text{O}$  is best suited for mountainous watersheds to analyze springs.

In a study in Uttarakhand, India, Deodhar et al. (2014) identified the effect of altitude on spring behavior, and guided the introduction of new recharge structures. Their results showed that the recharge structures introduced in two springs increased spring discharge by 72% and 145%.

These studies demonstrated that stable isotope techniques could assist in identifying spring sources and transit times, and in increasing the overall understanding of spring hydrology. They have highlighted the potential of stable isotopes in understanding springwater sources, recharge areas and human impacts on springs across varying geologic settings, especially for springs originating in inaccessible regions. Compared to single isotope studies, multi-isotope studies were able to identify different spring sources, including those originating from deep aquifers. In many instances, the spatial and temporal frequency of isotope analysis was limited due to logistical challenges, and hence large-scale inferences are limited. The cost of isotope analyses remains a constraint; however, they have become more affordable recently. Therefore, researchers are encouraged to carry out multi-isotope studies in the future rather than single isotope studies.

## **Analytical Methods**

Analytical methods rely on the power of logic and reasoning. They take advantage of established theories to extend the application of limited empirical data to spatial and temporal domains for which data are unavailable. Common analytical methods used in spring hydrology are reviewed below.

### ***Spring Hydrograph Separation***

Spring hydrograph separation methods are mathematical characterizations of the baseflow, which were originally developed by Maillet (1905), but have been substantially modified since then (Bonacci 1993, 1995; Padilla et al. 1994). In this technique, recession coefficients are estimated from spring hydrographs to provide information on the system's hydraulic and geologic parameters.

Kovács et al. (2005), and Kovács and Perrochet (2008) used spring hydrograph separation methods to understand spring sources in the Swiss Alps. Their results indicated that the recession process depended on the hydraulic properties and the size of the low-permeability blocks. Furthermore, the studies found that the hydrograph analysis method was better than other analytical methods (such as equivalent discrete-continuum models), which were inadequate for simulating the global response of mature karst systems. Valdiya and Bartarya (1989) investigated variations in spring discharge in the Kumaun spring in the Himalayas, by observing spring discharge for 29 years (1958 to 1986). They separated baseflow using the hydrograph separation method to determine any reduction in spring flow. Results from their study indicated that increased deforestation (by 13% in 22 years) and accelerated erosion have led to a 40% reduction in spring flow. Vashisht and Bam (2013) identified a recession in spring discharge in Ranichauri, a watershed in the Himalayan region, to quantify permeability and storage characteristics of underlying geology, which constrains flow. Subsequently, a discharge function was derived for this spring, which was up-scaled to characterize springs at the basin scale. In this particular instance, the recession curve had two discernible slopes, indicating two distinct ranges of permeability. Results indicated that the spring flow decreased with a decrease in rainfall.

The aforementioned studies conducted in the Himalayan region indicated that the stressors resulting in reduced spring flow include anthropogenic (deforestation) and natural (reduction in rainfall) variation, and the causal agents can be determined using analytical methods.

### ***Kernel Functions***

Kernel functions (Neuman and De Marsily 1976), which are a measure of the response of aquifers to unit stress, have been used to predict groundwater, spring flow and solute transport in karst systems. For example, Wicks and Hoke (2000) used kernel functions to identify sources of springs in the forests in Missouri, United States. Dreiss (1982) used linear kernels to understand karst spring hydrology and was able to predict the storm response of a spring.

### ***Integrating Historic Data of Multiple Parameters***

Many studies have used long-term data to analyze the hydrological regime in the Himalayan regions (Manandhar et al. 2012, 2014; Ma et al. 2010). However, only a few studies have focused on spring hydrology. For example, Mukhopadhyay and Khan (2014) analyzed 11 gauging stations between 14 and 48 years, and identified different common flow regimes in the Upper Indus River Basin. The study indicated a maximum contribution of 54% of snowmelt to annual streamflow and spring discharge. They predicted that the snowmelt from high altitudes contributed more to spring discharge than that



from mid-altitudes. They concluded that ongoing and future variations in temperature and precipitation would result in long-term reductions in spring discharge in the Upper Indus River Basin.

Many studies indicated that the springs are affected by variations in rainfall and anthropogenic activities occurring in the recharge area (Rawat and Rawat 1994; Rawat 1999; Negi 2002; Negi and Joshi 2004; Joshi 2006; Rawat et al. 2011; Rawat 2012; Pant and Rawat 2015). Negi et al. (2007) evaluated relationships between rainfall, physiography, lithology, slope and aspect, land-use practices, vegetation, altitude, soil type, anthropogenic interference, and water yield and quality of twelve Himalayan springs. They observed that peak rainfall coincided with peak discharge, indicating rapid infiltration to an unconfined aquifer in the region. The study further characterized springs using hydrogeological and geomorphological features, identified recharge zones and suggested conservation measures for augmentation of spring discharge. The study concluded that smaller recharge areas are highly profitable for augmenting spring discharge, and are more readily protected and managed.

Mahamuni and Kulkarni (2012) compiled the following data from 15 Himalayan springs: location, elevation, discharge, pH, salinity, temperature, TDS, and Electrical Conductivity (EC). Their study found that reduced rainfall, unevenly distributed rainfall and reduced infiltration may lead to a reduction in spring discharge, and that spring discharge is highly dependent on aquifer properties. Hence, they concluded that gaining an understanding of the “mountain aquifers” is key to effective management of Himalayan springs.

Jeelani (2008) monitored 40 springs from 1982 to 2005 using a velocity-area method in the Kashmir region of the Himalayas, and identified a reduction in spring discharge. The study also used chloride methods to analyze spring recharge. Based on the results, the springs were classified as karst, alluvium, karewa (belonging to the karewa sediments group) and warm springs. In the summer, snowmelt was the highest contributor to spring and stream discharge. Spring discharge was more highly correlated with snowmelt and snow area rather than precipitation. Snow cover data were used to assess the relationship between spring discharge and a reduction in snow cover.

Andermann et al. (2012) analyzed 30 years of climate and discharge data, and identified precipitation-discharge hysteresis loops in the glaciated and un-glaciated regions of Nepal. The study indicated the existence of a deep groundwater contribution to Himalayan springs. Agarwal et al. (2012) monitored 50 springs, nine rain gauges and two river gauging stations in Uttarakhand, India, for 11 years, and estimated lag times of 1 to 30 days between precipitation and spring discharge. The flow lag times were used to demarcate areas for water retention structures to increase water availability.

Singhal et al. (2010) used a combination of geophysical techniques (resistivity profiling and electromagnetic surveys), isotope techniques (to find the age and recharge of springwater) and well monitoring data to assess groundwater depletion in Uttarakhand, India. The study claimed that the current rate of groundwater development is not sustainable and recommended the construction of check dams to increase spring discharge.

The aforementioned studies demonstrate the range of methods that are available to combine a vast array of indicators monitored for varying durations to inform the behavior of springs.

### ***Mapping of Springs***

Maps are a diagrammatic representation of an area showing physical features. When data are limited, satellite remote sensing techniques have been used to develop datasets at sub-basin and basin scales. Other tools used to develop maps include artificial neural networks (Corsini et al. 2009; Mocior et al. 2015), geographic information systems (GIS) (Remondo and Oguchi 2009; Pourtaghi and Pourghasemi 2014), bivariate statistical models and GIS (Moghaddam et al. 2013), surveys (Barquín and Scarsbrook

2008), analytic hierarchy process and GIS (Rahmati et al. 2014), binary logistic regression method and GIS (Ozdemir 2011), cluster analysis (Michalik 2008), frequency ratio and certainty factor models (Razandi et al. 2015), and near surface temperature measurements (Eppelbaum et al. 2014).

In recent years, many state agencies have developed maps of springs by integrating available data. For example, the Sikkim government produced a spring atlas and manuals (*Dhara Vikas*) for the Sikkim part of the Himalayan region (Government of Sikkim 2014). Such mapping demarcates spring recharge areas and its watershed boundaries. Spring watersheds are often referred to as springsheds, spring-scapes, and spring landscapes (Fellingina 1996; Mahamuni and Kulkarni 2012; Government of Sikkim 2014). Products similar to *Dhara Vikas* are needed for other parts of the Himalayas, where geologic setting, population, land use and language differ.

Israil et al. (2008) used geo-electrical techniques in a piedmont zone of the Himalayas to map aquifers. They correlated the Vertical Electrical Sounding (VES), Electrical Image Profiling (EIP) and Time Domain Electromagnetic (TDE) techniques to predict the extent of aquifers and spring discharge patterns.

Mahamuni and Kulkarni (2012) produced maps and inferred a site-specific relationship between spring and recharge area. The study also indicated the characterization of the springs while mapping aids in recharge area protection. They advised consultation with locals during both the dry and monsoon seasons to identify seasonal or perennial springs.

The springs in the Himalayan regions are mostly depression springs, formed due to undulation of the topography (Mahamuni and Kulkarni 2012). Hence, regional geological maps can aid in understanding the rock type, their structure and texture, which will in turn increase understanding of the hydrogeology. Thus, topography and geology can aid in spring mapping exercises in the Himalayan region.

### ***Water Budget Method***

The water budget method is based on quantifying water inputs (e.g., precipitation) and outputs (e.g., discharge, evapotranspiration) in a watershed. Valdiya and Bartarya (1989) used the water budget method as per Thornthwaite and Mather (1955) to estimate recharge for springs in the Gaula catchment, located in the Kumaun Lesser Himalayan region in India. The study reported that only one-third of the rainfall recharges the springs in the region. In addition, the study estimated that spring discharge decreased between 10 to 76% in the region between 1958 and 1986. The reduction in discharge was attributed to changes in land use and anthropogenic activities. This has also led to a decrease in river discharge in the Lesser Himalayan region, which has impacted livelihoods in this region. Isotope analysis could have helped in better partitioning the spring and river discharge components, but the costs for such an analysis was high.

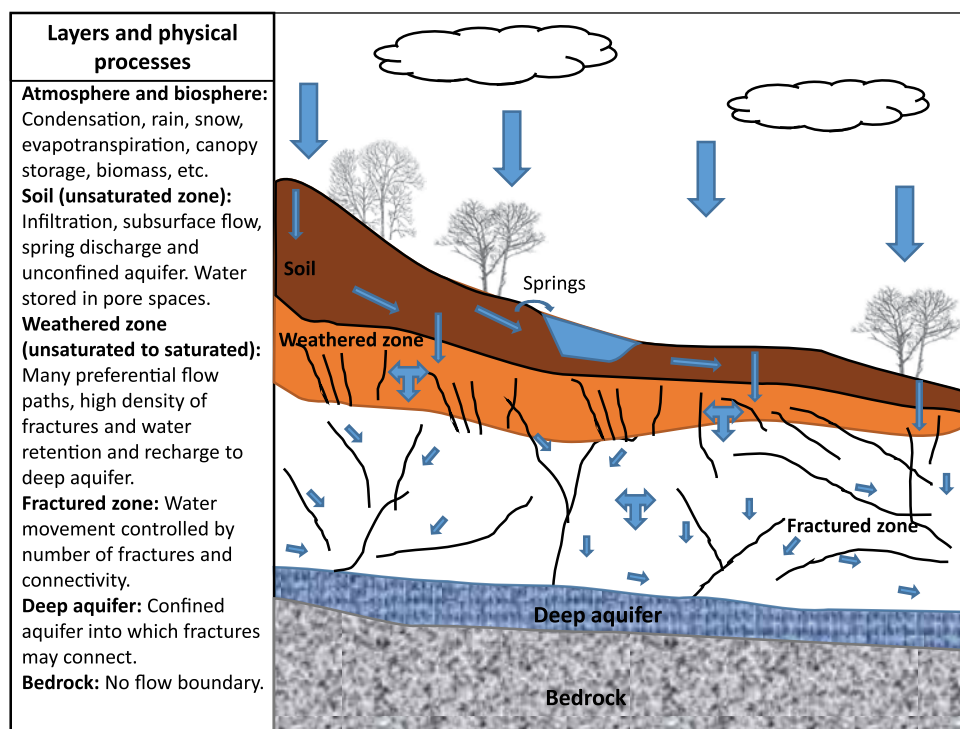
### ***Conceptual Models***

Irrespective of the extent of the data available, it is essential to formulate a conceptual model for the study region a priori, and regularly update it as new data and information become available. Conceptualization involves identifying and describing the processes that control or influence the movement and storage of groundwater. The conceptualization should consider the physical processes, and resulting heads and flows. In this regard, it provides information on how spring flow utilization is expected to impact on the groundwater and surface water bodies that depend on groundwater. The conceptual model must explain (qualitatively and quantitatively) all observed groundwater behavior in the region. In many cases, the conceptual model may not be unique (i.e., different conceptual models can explain all observations). Therefore, it is essential to evaluate alternative conceptualizations.

A conceptual model includes fundamental hydrogeological concepts to understand and visualize processes such as recharge and discharge, constraints to groundwater flow and directions of regional flows (Figure 1). They also aid in improving the understanding of topographic features (altitude, inclination, slope, etc.), soil (porosity, texture, structure, etc.) and geology (fractures, faults, bedrock, etc.) that define the properties of the aquifer. Conceptual models also help in identifying suitable monitoring and optimal sites for spring and watershed interventions.

In recent years, the use of conceptual models in the Himalayan regions has increased the awareness of spring sources, and has aided management and restoration efforts (Mahamuni and Kulkarni 2012; Government of Sikkim 2014).

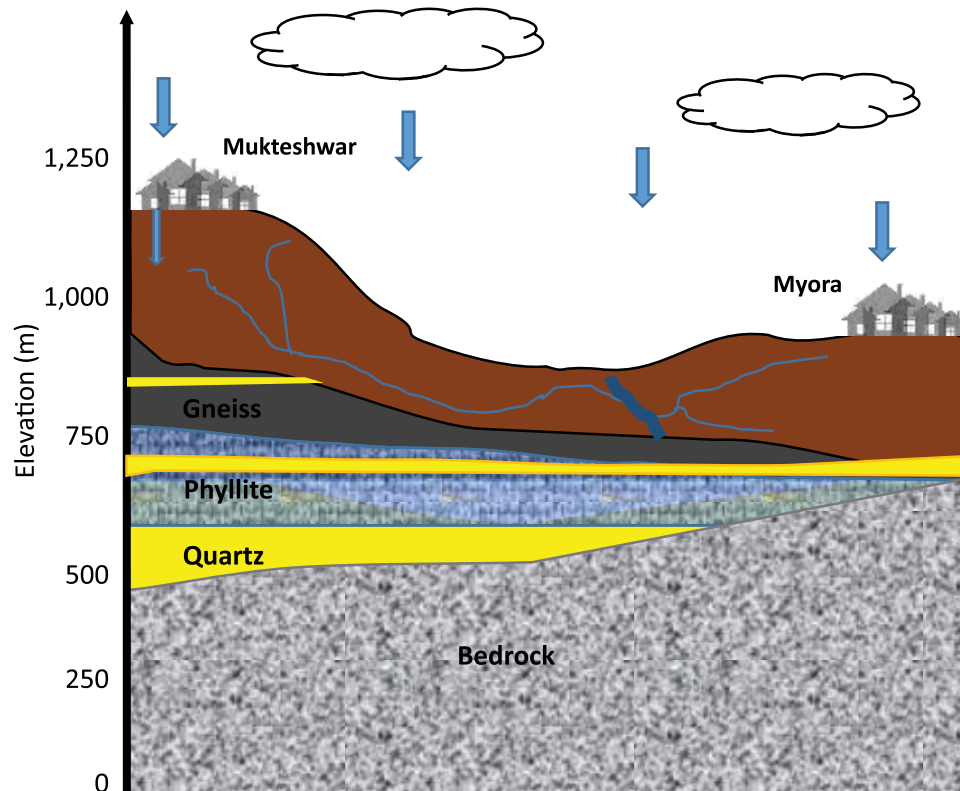
FIGURE 1. Example of a conceptual model.



Mangin (1984) constructed conceptual models for carbonate aquifers in France to infer the organization of conduits and groundwater flow, including periodic pulses of water into and out of subsidiary voids and channels. White (2002, 2003) used lithologies and field observations to construct conceptual models for aquifers that showed recharge, discharge and storage areas in the Rocky and Colorado mountains. The studies found that mountainous areas with karst aquifers have recharge occurring in four stages, i.e., (i) surface to spring aquifers, (ii) overland flow into conduits, (iii) precipitation infiltration, and (iv) from perched water sources to springs.

In a study by Kulkarni (2008), conceptual models were used to assist in the estimation of geohydrological controls on water resources in Nainital District in the Himalayan region of India. Of the conceptual models, Figure 2 shows a model constructed for the study site between Myora and Mukteshwar. The conceptual model shows the presence of quartz outcrops at various locations in the study area, which are important points for spring discharge.

FIGURE 2. Example of a conceptual model in Nainital District in the Himalayan region, located in Uttarakhand state of India.



Source: Kulkarni 2008.

### ***Mathematical Models***

Over the past decade, many mathematical modeling approaches have been used to understand spring hydrology. The models are based either on governing equations for conservation of mass and convective processes in a porous media or on empirical data from watersheds. The former category includes models discretized in time and space (numerical models) or both dimensions lumped together (analytical models). Analytical models have many assumptions and approximations (Freeze 1971; Ghasemizadeh et al. 2012). Numerical models discretize time and space, and use numerical methods to solve governing equations of flow to simulate hydraulic heads, and approximately quantify recharge, discharge and storage.

In a review of groundwater models applied to the North Coast Limestone aquifer system of Puerto Rico, Ghasemizadeh et al. (2012) found that lumped models used more approximations than distributed models, and hence transport of point source contaminants could not be evaluated. On the other hand, the distributed models were capable of simulating more complex flow mechanisms (including matrix flow and conduit flow). Ghasemizadeh et al. (2012) further recommended that researchers need to identify the modeling methods in the research needs with careful examination of the limitations and applicability of each model.

In a case study of the Barton Springs Edwards Aquifer (USA), Scanlon et al. (2003) investigated the potential of lumped and distributed equivalent porous media approaches to model flow in karst springs. The modular three-dimensional finite-difference groundwater flow (MODFLOW) code (McDonald and Harbaugh 1984) was used as the distributed parameter model, in which field measurements were input to setup the initial model. They also developed a five-cell lumped parameter model for comparison. They showed that equivalent porous media models can predict

spring hydrology in the highly karstified Barton Springs (USA) region satisfactorily. The distributed model was slightly better than the lumped model owing to the high quality of the field datasets.

Doummar et al. (2012) used an integrated catchment model (MIKE SHE [DHI 1998a, 1998b]) to understand the flow processes in a large-scale karst geologic system in the Gallusquelle spring (Southwest Germany). Their results indicated that soil type had the most effect on groundwater recharge by influencing infiltration and evapotranspiration. They also identified that peak discharges occurred when the soil was saturated.

Chinnasamy (2012) used high frequency groundwater and stream discharge data to calibrate and validate a HYDRUS code (Chinnasamy and Hubbart 2014a) and a MODFLOW code (Chinnasamy and Hubbart 2014b) for the Baskett research area, Ozarks Forests, Missouri, USA, which is characterized by a karst geologic setting. Remote sensing images were used to identify land-use type and recharge rates, while micro-climate stations were used for meteorological data. The model was able to predict the gain/loss behavior of the study area, and locate the percentage of streamflow that was losing water to the aquifer.

Tritz et al. (2011) used a two-reservoir conceptual model with a hysteretic transfer function for hydrological modelling of karst catchments in the Durzon spring (France). They showed that, with a hysteretic transfer function, the model performed better in predicting spring hydrology when compared with other models.

The aforementioned studies show that, even though modeling challenges exist in estimating the hydrological properties of springs, many modelers were successful in using models to improve the understanding of spring hydrology. For improved modeling, White (2003) indicated that future spring modeling exercises should include modules (i) that capture all flow mechanisms and interactions between components at aquifer scale, (ii) for sediment transport within the aquifer, and (iii) for estimating contaminant transport and pollutant loading in aquifers. However, the data needed for the aforementioned analysis is limited and hence studies mostly make assumptions on aquifer properties. Therefore, the level of sophistication of the model should be determined, in part, by data availability, as without adequate data the application of detailed models can be limited or misleading. Key studies on spring hydrology and the methods used are listed in Table 1.

TABLE 1. Key studies on spring hydrology and the methods used.

Reference	Catchment/region	Method	Key findings
Hickey 1984	Pinellas County, Florida	Variable pump rate	Darcian flow through semi-confined aquifers were confirmed. Results were later used for springs
Jeelani et al. 2011	Kashmir Valley, western Himalaya, India	Water chemistry	Streams recharge springs in the region
Jeelani et al. 2010	Liddar watershed, northwest Himalaya, India	Isotope analysis	Rainfall is the major source of water in springs
Vashisht and Bam 2013	Ranichauri, a watershed in the Himalayan region, India	Spring hydrograph	Reduction in spring discharge is due to climatic factors
Kovács et al. 2005	Swiss Alps	Spring hydrograph analysis	global response of mature karst systems could be estimated
Government of Sikkim 2014	Sikkim, Himalayan region, India	Conceptual model and spring mapping	Springsheds and boundaries aid in focusing the management work
Chinnasamy 2012	Ozarks forests, Missouri, USA	Mathematical models	Stream water alternates between source and drain for springs
Doummar et al. 2012	Germany	MIKE SHE simulation model	Soil properties are the controlling factor for spring discharge

## LESSONS FROM PAST WATERSHED INTERVENTIONS

To augment spring discharge in vulnerable regions, many watershed interventions have been implemented in the Himalayan region over the years (Singh et al. 2014). Lessons from past interventions can be used to guide future investments. Various approaches have been used for evaluating the impact of watershed development programs on water availability, downstream-upstream linkages, etc. (Garg et al. 2012).

The *Dhara Vikas* handbook on springshed development (Government of Sikkim 2014) recommended that the success of development projects are to be evaluated by comparing spring discharge during low-flow/dry periods before and after installation of interventions. Hence, it is important to have baseline data on historical spring discharge, and compare these against two to three years of spring discharge data that were collected after the intervention was installed.

Tambe et al. (2012) observed a 50% reduction in spring discharge in Sikkim within a decade. They also reported that springshed development interventions increased spring flow by 230%. However, they noted that identifying recharge areas, developing local capacity, incentivizing rainwater harvesting structures in farmers' fields and sourcing public finances remain constraints to springshed development.

A report on a springwater recharge program conducted by the Central Himalayan Rural Action Group (CHIRAG) (CHIRAG 2012) studied five springs in the Kumaun region of the Himalayas. The springs were monitored in 2009 and again after the introduction of water recharge structures in 2010. The water recharge structures consisted of percolation ponds, *khals*, terrace levelling, terrace bunding, and drainage to recharge structures. The study reported that the introduction of the recharge structures quadrupled the low-flow/dry-season spring discharge. The storage structures were also used for washing clothes and as watering holes by cattle. In addition, the study indicated that many new and old springs were revived due to the storage structures.

In many instances, a successful practice applied at one site is transferred to other sites (one-size-fits-all approach), even though there are considerable differences in geology, climate and hydrologic setting (Negi 2002). For example, afforestation, which is beneficial in gentle landscapes, is implemented on steep landscapes where their benefits are questionable. Furthermore, knowledge of channel network geometry is important at the meso-scale, but hillslope hydrology is more important at a sub-catchment scale. Such practices may not completely influence spring discharge due to variation in the underlying hydrogeology. For example, Bruijnzeel and Bremmer (1989) indicated that vegetation cover exerts control over water yield only in catchment areas less than 500 km<sup>2</sup>.

Bartarya (1991) proposed 'spring sanctuaries' to enhance recharge to springs. According to this study, spring sanctuaries (ponding structures that are fenced and protected to allow water to recharge springs) need to be placed in hillslopes, ridges, alluvial fans and former landslide scars (as opposed to flatland terrain). The study also recommended limiting the use of the mountain land as follows: top third for forest, middle third for pastures and the lower third for agriculture. Even though the author had insights and plans for future development, the impact of such plans may be limited due to assumptions being made without physical data to support hypotheses.

In a series of reviews, Calder et al. (2008a, 2008b) emphasized the need for a revision of watershed development policies and watershed impact assessment methodologies in India. They made this inference within the context of two watersheds in Karnataka, where the Hydrological Land Use Change (HYLUC) model (Calder 2003) was used for assessment. According to their review, future development plans should include changed flow conditions, externalities, ecosystem services and downstream environmental flow regulations. In addition, development plans based on such information can aid in influencing site-specific springs.

Kumar et al. (2012) conducted a study on the effectiveness of watershed development and groundwater recharge interventions in the Upper Bhima, a sub-basin of the larger Krishna River Basin. Their modeling results indicated that the downstream communities will be highly impacted from the interventions, and hence their impacts should be considered when installing rainwater harvesting systems in upstream locations.

It is necessary to assess and overcome socioeconomic constraints in an area before implementing watershed interventions. Pavelic et al. (2015) noted that the impacts of watershed development projects are site- and scale-specific, and must consider upstream and downstream impacts. In a study conducted in the Chinnahargari watershed in Karnataka, India, Batchelor et al. (2003) indicated that development projects can aid in water availability, but will increase the ongoing water accessibility and inequity issues. The study indicated that the poor and marginalized were severely affected. It also claimed that the emphasis should change from development to management of water in order to satisfy demands from the highest economic and social value sectors.

The aforementioned studies show that watershed development projects should be introduced after including the fundamental hydrogeological principles, and weighing the physical, social and economic benefits concurrently. In addition, these studies indicate the need for scientific validation of watershed development projects, in order to gain confidence in future investments and to understand socioeconomic stressors.

## **RECOMMENDATIONS FOR THE FUTURE**

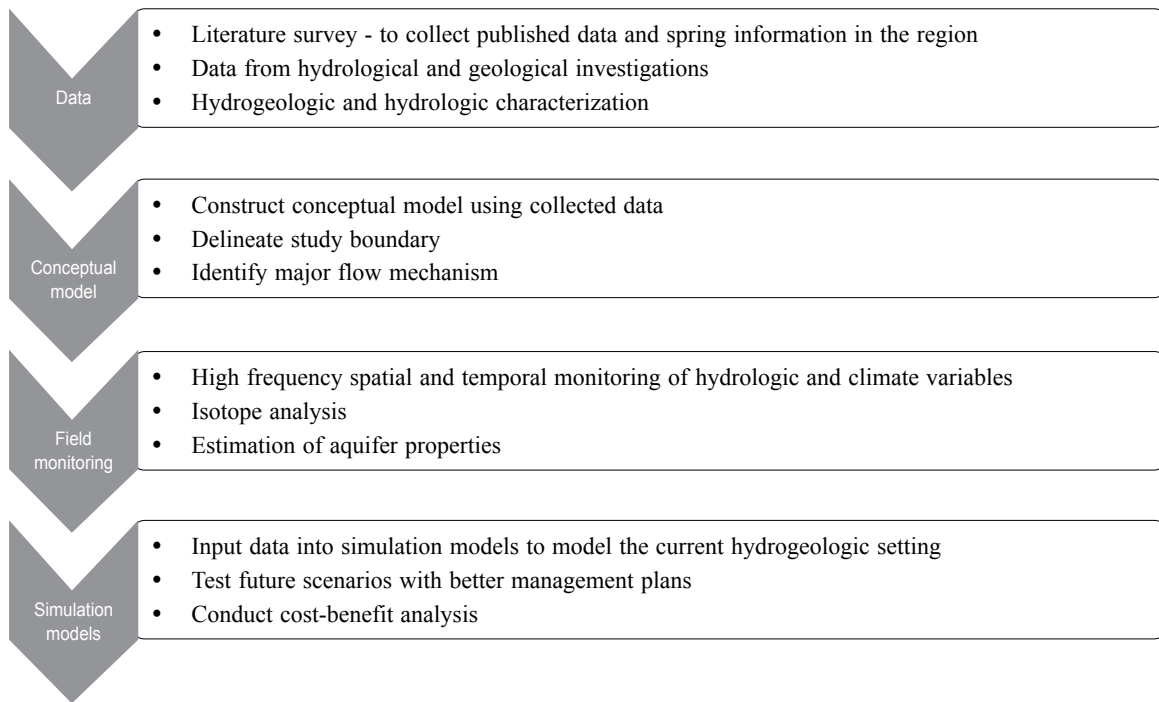
Kresic and Stevanovic (2009), and Kresic and Bonacci (2010) stated that any workable, realistic plan drawn for the management of springs must fulfill the following prerequisites: (a) hydrogeologic and hydrologic characterization of the spring type, drainage (discharge) and recharge area, and recharge and discharge parameters, such as water quantity and quality; and (b) reliable and predictive modeling of spring discharge and water quality, which can be achieved by collecting discharge and quality data of springs.

Therefore, it is important to have a good conceptual model of the dominant flow mechanisms in the complex Himalayan region. The conceptual model can be built using the available geology maps, field observations, borehole (lithologs) data and spring locations. Stratigraphy maps can be produced using available borehole data and geology extent maps. Probing for non-linearity in pumping or discharge can be used to identify the interconnectivity of spring channels. The conceptual model needs to be supported by thematic maps produced from remote sensing images, which were ground-truthed using field visits. In addition, many maps produced by previous studies or reports can be used as a baseline for future projects.

An analysis of historical rainfall, spring discharge, water quality and temperature data are mandatory for the region. Data on water chemistry (e.g., calcium, nitrate, etc.) and physical properties (temperature, pH, TDS, electrical conductivity, etc.) could also aid in understanding water sources. Rainfall and streams should be gauged to understand the status of the local hydrologic regime. As done globally, new researchers in this region should include stable isotope techniques to demarcate spring recharge areas. Analysis of available data, in conjunction with indigenous knowledge, are crucial to devise site-specific management strategies. In addition, spring discharge monitoring plans need to be formulated with the community, so that they are also included in spring protection measures and can sustain the development projects for longer periods.

Finally, with the above understanding on spring hydrology and estimation of aquifer properties, future studies should aim at incorporating the findings in simulation models for spring hydrology. These models can aid in understanding the interactions between processes, identifying key flow pathways, and testing possible scenarios that incorporate future developments, population growth and climate change. In addition, the user-friendliness of computer models will enhance its adoption by government agencies and policymakers. A flowchart to explain the steps involved in conducting research on spring hydrology in the Himalayan region is shown in Figure 3.

FIGURE 3. Recommended flowchart for research on spring hydrology in the Himalayan region.



## CONCLUSIONS

Springs are the most important freshwater source in many Himalayan villages. The causes for a decrease in spring discharge in the Himalayan region are attributed to population growth, increase in groundwater pumping, erosion of the topsoil, erratic rainfall patterns, climate change trends (especially in rainfall and temperature), deforestation, forest fires and development activities. Watershed interventions can aid in augmenting spring discharge. However, site-specific data are needed to implement successful watershed interventions. In particular, interventions to combat decreases in spring recharge involve detailed field investigations with the aid of hydrogeological maps, and conceptual and mathematical models. In the current review, almost all studies urged the need for active community participation in spring protection and recommended interventions such as artificial rainwater harvesting measures, afforestation, and demarcation and protection of recharge zones from human activity.

Hydraulic and geometric information on springs can be obtained from classical hydrogeological survey data, hydrological observation data, geological survey data, speleological and geophysical



observations, and chemical analysis and discharge measurements. However, only limited information will be available if a single method is used, due to the heterogeneity and complexity associated with spring systems. Therefore, an approach which includes reconnaissance surveys, data monitored directly (stream and spring discharge) and indirectly (tracers), and simulation models can provide an integrated and holistic understanding of spring hydrology within the Himalayan region. It is also necessary to understand the limitation of each method before using it in the holistic approach. Information gathered via this approach will aid in increasing the understanding of hydrogeologic processes associated with Himalayan springs, and can lead to scientifically validated watershed intervention and monitoring plans.

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