Mapping of groundwater spring potential zone using geospatial techniques in the Central Nepal Himalayas: A case example of Melamchi–Larke area

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Studies assessing the groundwater spring potential in the Himalayan mountain slopes are very important for sustainable water resources management and build climate resilience in mountains, but such studies are few in the Himalayas. Hence, this paper attempts to identify the groundwater spring potential zone in the Central Himalayas of Nepal. About 412 groundwater springs were surveyed, which were mainly originated from the weathered, jointed or fractured rock aquifers in the high-grade metamorphosed rocks. Eleven influencing factors, viz., altitude, slope gradient, slope shape, relative relief, flow accumulation, drainage density, geology, lineament density, land use and vegetation density were considered in assessing the groundwater spring potential using the weight of evidence method. Weight indicating the probability of groundwater spring occurrence on multiple classes of each factor was calculated and finally summed up to determine the groundwater spring potential. Gentle slope, low relative relief, high flow accumulation, north- and east-facing slopes, denser lineament density, altitude class of 1500–2500 m, high vegetation density, and forest demonstrated a higher likelihood of spring occurrence. Validation of the groundwater spring potential map was successful, which implies the method can be replicated in a similar biophysical environment, where the hydrogeological or geophysical surveyed data is not available.

Keywords. Groundwater spring; weight of evidence; hydrogeology; Himalayas.

1. Introduction

Groundwater spring has been used by mountain people since time immemorial to meet the basic needs of the households, livestock and irrigation. These natural springs represent the groundwater storage within the catchments, which form an important component of the Himalayan water budget (Andermann *et al.* 2012). It is estimated that the flow of water through the fractured basement in the Himalayas is as approximately six times the annual contribution of glacier and snowmelt, which is in contrary to the contemporary notion that held rain, ice and snow as major

contributors for the discharge of the large rivers in the Himalayas (Bookhagen and Burbank 2010; Immerzeel *et al.* 2010).

Like many principal aquifers around the world (Alley *et al.* 2002; Brekke 2009; Gurdak *et al.* 2009), the groundwater resources in the aquifers of mountain watersheds of the Himalaya are under the risk of depletion due to human and climatic stress (Valdiya and Bartarya 1989; Tambe *et al.* 2012; Mukherjee *et al.* 2015; Chinnasamy and Prathapar 2016). Degradation of the catchments, land use change and extensions of development infrastructures have disrupted the hillslope hydrology largely in the Middle Mountains of

Nepal. This has led to drying up of spring or reduction of flow regime during the dry months (Gurung and Nepal 2007; Peking University TU 2013; ICIMOD 2015; Chinnasamy and Prathapar 2016; Chapagain *et al.* 2017). Climate change and variability are emerging as a new threat to ground spring water depletion (Bates *et al.* 2008; Green 2016). Similarly, recent 2015 earthquake in the Central Nepal Himalayas is reported to have seriously disrupted local water budget as evidenced by drying up of over 5000 groundwater springs (<https://globalpressjournal.com/asia/nepal/water-sources-run-dry-nepal-2015-earthquake-forcing-people-leave-ancestral-villages-hike-faraway-wells/>). Scientific studies indicate that the earthquake-induced crustal deformation and ground shaking alter stream flow and water levels in the wells through consolidation of surficial deposits, fracturing of solid rocks, aquifer deformation and the clearing of fracture-filling materials (Montgomery and Manga 2003; Galassi *et al.* 2014).

Notwithstanding the above facts, groundwater spring in the Himalayas is poorly understood and insufficiently mapped, and the potential occurrence of groundwater spring in the Himalayas is little studied (Chinnasamy and Prathapar 2016; Sharma *et al.* 2016). The occurrence of groundwater at any location on the earth is not accidental, but an effect of the interaction of the climatic, geological, hydrological, physiographical and ecological factors (Andermann *et al.* 2012; Abuzied and Alrefaee 2017). This interaction in the highly deformed Himalayan terrain (resulting from folding, faulting, and development of joints and fractures), which experiences a high rate of weathering and mass movements, microclimatic and ecological variations and change in the landscape, is yet adequately understood (Bookhagen and Burbank 2010; Immerzeel *et al.* 2010; Andermann *et al.* 2012; Mahamuni and Kulkarini 2012). Lack of adequate data on geology and structure, soil, geomorphology and groundwater hydrology makes spatial prediction or mapping groundwater spring potential zones even more difficult. Some earlier studies attempted to predict groundwater potential zones by examining spring sources' associations with chosen *in situ* biophysical terrain factors (Greenbaum 1992; Mukherjee 1996; Marklund and Wörman 2007; Pradhan 2009; Oh *et al.* 2011; Moghaddam *et al.* 2015), which have been derived as direct and proxy indicators from geospatial data sources. In this study,

similar attempt is made to identify the groundwater spring potential zones in the Higher Mountain portion of the Himalayas in Nepal. Identification of such potential zones will invite scientific research studies, which aim to understand the groundwater hydrology vis-à-vis the aforementioned factors. Validated groundwater spring potential maps can be used for catchment and springshed management as a component for the water resource conservation and management strategy in the mountains.

1.1 Study area

The study area lies in the 50 km northeast of Kathmandu valley. Geographically, it is located in the High Mountain region with a relief between 900 and 6100 m resulting in varying temperature and rainfall regimes (figure 1). It comprises the watersheds of the Melamchi in the west, Yangri in the middle and the Larke River in the east. These three watersheds are the part of the Indrawati River Basin. Helambu, Baruwa, Bhotang and Kiwool are the prominent areas of the Melamchi–Larke area. The study area delineated for groundwater spring potential mapping covers 320.3 km².

1.2 Geological setting

The geology of the study area comprises the higher Himalayan crystallines containing predominantly the large masses of augen and banded gneisses, interbedded with schists or/and quartzites. These rocks record the higher grade of metamorphism (DMG 2005; Dhital 2015). Based on the lithologic characteristics, the rocks are classified into the following formations (DMG 2005).

The Shermathang Formation is made up of interbedded feldspathic schist, augen gneiss, quartzite and biotite–feldspathic schists. The Pangang Formation constitutes thick-bedded banded gneiss and fine-grained schist. The Dhadkhola Gneiss represents augen gneiss with thin bands quartzite, schists and migmatitic gneiss. The Gyalthung Quartzite comprises medium- to thick-bedded grey to dark garnet–biotite quartzite and fine-grained biotite schist. The Simpani Formation constitutes kyanite–biotite schists, migmatite and biotite–feldspathic schist with bands of quartzite. Notable alluvium deposits comprising river terraces at Mahankal area at the south is observed (DMG 2005). NW dipping thrust runs through Ichok in the south and Narpu in the north in a

Figure 1. Study area: Melamchi-Larke (part of the Indrawati Basin).

curvilinear pattern, which is offset by the NW–SE fault in the further north and then branches into two SW–NE trending imbricate thrusts (figure 2). The bedrocks are also dipping towards the NW.

Melamchi-Larke area lies north to the Main Central Thrust (MCT), an intracrustal thrust, which separates Lesser Himalayas from the Higher Himalayas. The area adjacent to MCT and other imbricate thrusts is tectonically highly deformed and experiences high accumulation of stress, which is released through a number of tectonic events and structural readjustment producing faults, joints

and fractures and foliations. Well-developed two to three sets of joints are seen and numerous randomly oriented and locally controlled joints and fractures owing to crustal deformation are developed on the bedrocks. Various irregular-shaped voids and fractures that appear to originate as joints or foliation-parallel partings/openings are also observed (figure 3).

These highly sheared and fractured bedrocks are also deeply chemically and biologically weathered on the surface, which is occupied by thick vegetation or cultivation zones on the gentler slopes,

Figure 2. Geological map of the study area.

Figure 3. Gneiss exposure in Melamchi area with different joint sets, J_1 as the foliation plane and J_2 and J_3 as other joint sets along with random joints. These joints provide suitable conditions for groundwater flow.

i.e., $\leq 35^\circ$. Downslope transport of soil and weathered rocks accumulates as colluvium in the flow convergence zones or colluvial fans in slope breaks

or could be transported by streams and river and deposited as alluvial fan or bar deposits in the valleys.

1.3 Geomorphology

The study area adjusted to a homoclinal rock structure in which the bedrock typically dips towards the NW at $20\text{--}50^\circ$ angle. About 60% of the area lies above the steep slope, i.e., 35° , 31% between 15° and 35° , 5.3% between 5° and 15° slope. The rest of the area is occupied by gentler slope, i.e., $<15^\circ$. The relief is very strong, whose amplitude is about 32–35% at length distances between the valley floor and the ridge in the middle reaches of all three major rivers namely, Melamchi, Yangri and Larke Rivers. Snow-covered area and bare rock, mid-upper slopes and ridges, steep narrow in-valleys, and the river valleys with relatively wide terraces are the major physiographic regions. The major north–south trending ridges, which

divide the waters of the three principal rivers, and the subparallel ridges demarcating divides of major tributaries developed on major joints are the striking physiographic characteristics.

1.4 Climate and hydrology

The climate varies from subtropical to arctic type, within 40 km south–north range, which has led to variation in biophysical characteristics. The average temperature ranges from 25° to 11°C from subtropical to alpine location. The observed temperature trend between 1975 and 2010 recorded at Nagarkot meteorological station (SI1043) (on the watershed divide of the Melamchi River in SW at 1905 m asl) showed that the daily maximum temperature increased by 0.01°C/yr and the daily minimum temperature by 0.05°C/yr. Increase in average duration of warm spells over the observed period was +0.02 d/yr (Pradhan *et al.* 2015).

The average yearly precipitation in the study area ranges from above 3000 mm at higher elevations (Sarmathang, 2600 m asl) to 1728 mm at the lowest elevation (Melamchi Bazar, 878 m asl). More than 85% of the precipitation is concentrated during the monsoon period, i.e., the middle of May to middle of October. Nearly half the rainfall is received in July and August. The average annual potential evapotranspiration is about 954 mm (WECS/IMWI 2002). The relative humidity varies from 60% in the dry season to 90% in the rainy season, with an average of 75%. Pradhan *et al.* (2015) observed some long-term trends in the pattern of the rainfall between 1975 and 2010 at Nagarkot, with annual fluctuations. The total annual precipitation on wet days increased by 3.33 mm/yr, the monthly maximum 1-d precipitation by 0.36 mm/yr and the number of consecutive dry days by 0.85 d/yr. At the Sarmathang station, an increase in monsoon precipitation since 1999 and a decrease in winter precipitation since 2002 were observed with contrasting fluctuations showing an erratic pattern.

The climate change scenario of the Indrawati Basin, which covers the study area, indicates a projected increase of temperature by +2.0°C yearly, +1.5°C in winter and +2.0°C in summer under Representative concentration pathway (RCP) 8.5, respectively, by 2050 (Palazzoli *et al.* 2015). This projection is in agreement with that of Karmacharya *et al.* (2007) with little difference. The projection of precipitation has varied with studies (Agrawala *et al.* 2003; Palazzoli *et al.*

2015; Pradhan *et al.* 2015). Of the same basin precipitation in Palazzoli *et al.* (2015) was projected to decrease by −46.6% in winter, +15% in summer and +9.5% yearly. Comparatively, Agrawala *et al.* (2003) found −9.6% in winter, −18.1% in monsoon season and −13.2% annually in the Kosi Basin where the Indrawati Basin also lies. Pradhan *et al.* (2015)'s projection shows 0.9% increase of precipitation of baseline in the 2020s, 1.4% in the 2055s and 3.0% in the 2080s. The study shows a clear increase in rainfall during the early winter months (65–111% of baseline by the 2050s) and a small increase in spring and early summer, but a decrease in late winter, mid-to-late summer and autumn.

The daily discharge of the Melamchi River recorded at Helambu River for the period between 1990 and 2007 reveals that almost every year, the predominant frequency of peak discharge is between 30 and 40 m³/s (cumecs) until 2005 and the peaks have started to decrease. During 1999–2000, there was a huge rise in the peak discharge during the monsoon reaching up to 120 cumecs, which was not recorded in the 20-yr period (figure 4). A huge difference in the monsoon and non-monsoon discharge can be observed in the range of >30 (monsoon) to <5 cumecs (non-monsoon).

1.5 Vegetation and land use

The natural vegetation of the Melamchi Valley ranges from the tropical zone to the alpine pastures towards the north of Jugal Himal. The tropical zone (below 1000 m) is represented by Hill Sal Forest. Four forest types, viz., Chir Pine, Broadleaved Forest, Schima-Castanopsis and Castanopsis-Laurel. Barren, rocky terrain, snow and glaciers in the alpine parts cover more than 40% of the study area followed by natural forest (32%) and shrubs and bushes (17%) (figure 2). Agriculture comprises 8% of the total area, which is largely confined in the southern part, where most of the settlements are located.

1.6 Population

The study area has a population of 10,000 with an average household size of 3.9 (CBS 2012). The Tamangs, along with other caste-ethnic groups, are predominant in the lower part of the study area. Hyolmo is the dominant indigenous ethnic group in the upper part of the study area (CBS 2012). The

Figure 4. Daily discharge of Melamchi River at Helambu from 1990 to 2007 (source: Department of Hydrology and Meteorology (DHM), Government of Nepal).

major occupation of people living in this region is agriculture, acting as tourist guides, business and migrating to foreign countries as mostly labourers or semi-skilled workers.

2. Methodology

2.1 Past studies

Assessing groundwater spring potential has been given much emphasis in current times, as water has become a highly prized resource, which needs to be efficiently managed for sustainable use. Planners and engineers have been increasingly using round water potential maps to locate appropriate sites to implement resource explorations (Oh *et al.* 2011; Guru *et al.* 2016). Traditionally, the field survey was the method applied to survey the groundwater potential zones (Ganapuram *et al.* 2009). Mapping of groundwater potential zones using geographical information system (GIS) and remote sensing technology within each geological unit has become a useful procedure in current times. Several pioneering works were done in the mapping of groundwater potential, which used remote sensing (RS) and GIS (NRSA 1987; Salama *et al.* 1994; Krishnamurthy *et al.* 1996; Saraf and Choudhury 1998; Sener *et al.* 2005; Yeh *et al.* 2009). Using these spatial technologies, factors that governed the groundwater occurrence were mapped and combined to examine the groundwater recharge potential. Recent studies on groundwater potential evaluation (Solomon and Quiel 2006; Jha *et al.* 2007; Nobre *et al.* 2007; Tweed *et al.* 2007; Patil and Mohite 2014; Machiwal and Singh 2015; Moghaddam *et al.* 2015) have demonstrated the importance of using GIS and remote sensing with various methodological development. Some methods include integration of RS and

GIS and multi-criteria decision-making techniques, eigenvector method (Machiwal and Singh 2015), and bivariate statistical techniques (Oh *et al.* 2011; Ozdemir 2011; Patil and Mohite 2014; Moghaddam *et al.* 2015). Yeh *et al.* (2009) proposed a simple method which considered five major contributing factors: lithology, land cover/land use, lineaments, drainage and slope. The weights of factors contributing to the groundwater recharge are derived using aerial photos, geology maps, a land use database and field verification. Moghaddam *et al.* (2015) examined the groundwater spring potential map using a bivariate groundwater spring potential map and GIS in a watershed of Iran.

Exploration and identification of groundwater resources in Nepal started as early as 1967 under the government undertaking. Such activities are mainly concentrated in Tarai or Kathmandu valley using field survey (Pandey *et al.* 2010; <http://www.gwrdb.gov.np/publications.php>). Some studies using GIS and RS have assessed the groundwater potential in Kathmandu valley using GIS and RS (Pathak *et al.* 2009; Pandey *et al.* 2013). Reviewing the methods from the above studies applied to groundwater potential mapping, the current study will use GIS-based statistical model, i.e., 'Weight of Evidence' by assessing the association of the occurrence of the groundwater springs with *in situ* parameters that influence groundwater in the High Mountain Region of Central Nepal.

2.2 Data types and sources

An inventory of all the springs of the study area was done using GPS during the field survey on site. The survey was conducted below 3000 m up to the settlement limit of the watershed. Above that elevation, local people have no

information and the entire area lies within the Langtang National Park, covered by dense forest. Rocky land with the steep slope has no easy access also.

While conducting the GPS survey, the assistance of local persons who knew about the location of springs in each settlement was taken. Expert knowledge and local information included was incorporated in the field survey. A standard checklist was prepared to include the on-site co-occurrence of topography and land use, and water discharge, access and use. Observed spring locations were used for two purposes. Eighty-five per cent of the spring locations were used for preparing a groundwater spring potential map, and the rest 15% were used for validating the map.

Eleven influencing factors related to spring occurrence and groundwater movement were considered in this investigation. These are slope gradient, slope aspect, altitude, relative relief, slope shape, flow accumulation, drainage density, lithology, lineaments, land use and vegetation density. These factors, which relate to groundwater springs potentials, were identified based on the previous studies, which have used the above factors in potential groundwater recharge mapping (Greenbaum 1992; Krishnamurthy *et al.* 1996; Mukherjee 1996; Saraf and Choudhury 1998; Shahid *et al.* 2000; Jaiswal *et al.* 2003; Sener *et al.* 2005; Shaban *et al.* 2006; Pradhan 2009; Oh *et al.* 2011; Ozdemir 2011; Moghaddam *et al.* 2015).

The first six parameters were analysed from the digital elevation model (DEM) with 20×20 m grid size. DEM was created using the elevation contours and spot height layers. The other parameters were obtained from the topographic maps (1:50,000), geological maps and satellite imageries. ArcGIS10.2 was used to extract or calculate the above layers either in vector or raster layers. Recent land use maps were produced by updating the land cover information of topographic maps through visual interpretation of Landsat-8 multispectral imageries. A 3×3 low-pass filter was applied to smoothen the imagery for enhancing the interpretation of Landsat-8 acquired in January 2016 (resolution: 30 m). Band combinations of 543, 562 and 642 were used for identifying land cover types, i.e., cultivated land, forest, bush, snow, rock and alpine barren. Training sample image pixels representing each cover type were selected from these band combinations for classifying the image. The

classification accuracy of $\geq 80\%$ was accepted. Normalised Difference Vegetation Index map using red and infrared band imageries of Landsat ETM was calculated for preparing vegetation density map (Jensen 2009). Natural linear or gently curvilinear geomorphic features expressing the geological structures such as faults, joints, fractures and lithological contact were extracted from the Landsat imagery by applying gradient filters such as vertical, horizontal and diagonal filters as well as by interpreting individual bands and colour composite images (Sabins 2007; Kolawole *et al.* 2016).

2.3 Weight-of-evidence (WoE) for groundwater spring potential mapping

The mapping of groundwater spring potential zone is based on data-driven method, where the weights of multiple classified layers are assigned by statistical procedures (Van Westen 2002). In this study, WoE, a statistical technique, is used to calculate the probabilistic relationship between the occurrence of spring as the response variable and multiple class terrain factors as predictive variables, which play a role in the occurrence of springs. A flowchart showing the groundwater potential mapping procedure is illustrated in figure 5.

WoE is the Bayesian approach in a log-linear form (Spiegelhalter 1986), where it estimates the relative importance of the evidence by statistical means. Prior probabilities and posterior probabilities are the important concepts of this approach. Former measures the probability that a terrain factor contains the S (spring) before taking a class of terrain factor (F) into account and its estimation is based on the S density in the study area:

$$P_{\text{Prior}} = P(S) = \frac{\text{Grids}(\text{Springs})}{\text{Grids}(\text{Total})}, \quad (1)$$

where $P(S)$ is the probability of having a spring, Grid(Springs) is the number of grids with springs on the map and Grid(Total) is the total number of pixels in the map.

Post-probability is then estimated according to the S density for each class of the F . It is a modification of earlier estimates of probability, which is expressed as:

Figure 5. A flowchart showing the groundwater potential mapping procedure.

$$P(S|F) = \frac{P(S \cap F)}{P(F)} = \frac{\text{Grids}(S \cap F)}{\text{Grids}(F)}, \quad (2)$$

where $P(S|F)$ is the posterior probability of occurrence of spring in each class of F .

Considering this concept, the weight of a class of factor, i.e., multiple class factor map based on the presence or absence of the spring (S) within the area (Bonham-Carter 1994) is calculated in log-linear form:

$$W_i^+ = \ln \left(\frac{P\{F|S\}}{P\{F|\bar{S}\}} \right), \quad (3)$$

$$W_i^- = \ln \left(\frac{P\{\bar{F}|S\}}{P\{\bar{F}|\bar{S}\}} \right), \quad (4)$$

where P is the probability, $\ln$ is the natural log, F is the presence of a class of factor, $\bar{F}$ is the absence of a class of factor for spring occurrence, S is the presence and $\bar{S}$ is the absence of the groundwater spring.

W_i^+ is used for those grids of a class in a multi-class factor map (F) to indicate the importance of the presence of the factor for the occurrence of springs (S). If W_i^+ is positive, the presence of the factor is favourable for the occurrence of springs; and if W_i^+ is negative, it is not favourable. Similarly, W_i^- is those for grids of a factor class to indicate the importance of the absence of factors. If W_i^- is positive, the absence of the factor is favourable for the occurrence of springs; and if W_i^- is negative, it is not favourable.

Table 1. Cross-tabulation of groundwater spring and factor maps.

Groundwater spring	Potential groundwater spring influencing factor	
	Present	Absent
Present	Ngrid1	Ngrid2
Absent	Ngrid3	Ngrid4

The positive and negative weights are calculated using table 1 (modified after Van Westen 2002). The area of interest of the factor maps is divided into grids of 200×200 m, where any spring location would be represented by a grid.

In GIS, the value of w^+ and w^- can be simply calculated using table 1 as follows:

$$w^+ = \log_e[(\text{Ngrid1}/(\text{Ngrid1} + \text{Ngrid2})) / (\text{Ngrid3}/(\text{Ngrid3} + \text{Ngrid4}))],$$

$$w^- = \log_e[(\text{Ngrid2}/(\text{Ngrid1} + \text{Ngrid2})) / (\text{Ngrid4}/(\text{Ngrid3} + \text{Ngrid4}))].$$

2.4 Final weight calculation

Since all of the maps are multi-class factor maps, containing classes, the presence of one class (e.g., one specific slope aspect unit) implies the absence of the other classes of the same map (e.g., slope aspect map). Therefore, in order to obtain the total weight of each factor, the positive weight of the class is added to the negative weight of the other classes on the same map. This is done by first

Figure 6. A simple model reflecting the hydrogeology aspect of the groundwater spring of the study area.

adding up all negative weights of the classes of one map and then deducting the negative weight of individual class (Van Westen 2002).

The final weight was then calculated as:

$$W = W^+ + \left(\sum W_{ij}^- - W_i^- \right) \quad (5)$$

in which $\sum W_{ij}^-$ is the total of all negative weights in a multi-class map.

3. Results and discussion

3.1 Groundwater spring inventory and hydrogeology

About 412 locations of groundwater springs were mapped in the study area. Out of them, 351 locations of groundwater spring were used for assessing groundwater potential areas and the rest 15% were randomly selected for validating the result. The source of all the groundwater spring is the rock aquifer, i.e., water stored in rock discontinuities, which include joints or zones of fracture concentration, and openings formed parallel to foliation

planes, voids and other weathered openings in the metamorphosed bedrock.

Stated earlier, the rocks underlying the study area are highly metamorphosed, the metamorphism process tends to reduce the porosity of rocks due to high pressure and temperatures. However, tectonic caused intense deformation in the study area has developed faults, deep-seated spaced joints, fractures, voids and cleavage foliations opening, which act as a water conduit and the rock aquifer. Frost action in the higher altitude through the repeated process of freezing and thawing has deepened and widens the rock joints and fractures, which provide porosity for subsurface water flow and storage. Recharge to the rock aquifer system occurs through infiltration of precipitation at the surface. The infiltrating water collects in the soil and weathered rocks, and recharges the underlying bedrock aquifer (figure 6). From the bedrock aquifer, water transmits through the conduits (rock discontinuities) to surface at downslope and emerge through openings or depressions as groundwater springs. Deep soil and weathered rock zone on the slopes below 40° serve as a groundwater reservoir that feeds the underlying

Figure 7. Groundwater spring emerging from the rock joints (left: Baruwa; right: Timbu Jharna, Timbu).

Figure 8. Groundwater spring seeping from the foliation joints of rocks in Baruwa area.

rock discontinuities, which also can store a substantial quantity of water. In the study area, a thick weather zone of >2 m was commonly observed; below this zone lies a transitional zone of saprolite where chemical weathering has changed the chemistry and created open spaces but not yet destroyed the rock's texture. This zone is generally more permeable than the overlying residuum, and in some places is more permeable than the underlying fresh rock and serves to store groundwater and allows it to move into fresh rock.

A simple model reflecting hydrogeology aspect of the groundwater spring has been shown in figure 6.

About 42% of groundwater springs are originated from water stored in joints and fractures, foliations of bedrocks. These springs emerged from the exposed bedrock from the outlet provided by

their discontinuities. Such joint/fracture springs occur due to the existence of jointed or permeable fracture zones in less permeable high-grade metamorphic rocks (figure 7). Springs emerging from the foliation openings of the exposed bedrocks were also common in the study area (figure 8).

Likewise, rest springs were spotted on soil or colluvium-covered slopes underlain by highly weathered zone (regolith) developed on the bedrock (figure 9). These springs have emerged through the process of discharge of water stored in the colluvium and regolith, as well as transmit of water to surface as a discharge through conduits connected to the rock aquifer (Winter 1998; Crawford and Kath 2005). Many of these springs are depression springs, which are formed when the water table in aquifer reaches the surface

Figure 9. Groundwater spring sprouting from the colluvium and regolith in the depression areas at Timbu of Baruwa (left) and Helambu area (right).

Figure 10. Groundwater spring issuing from the intensely fractured rocks (left) and saprolite containing macropore space in Baruwa Area.

due to topographic undulations (figure 10). Some springs emerging from colluvium or regolith, which lie on less permeable bedrock, are called as contact springs. Many springs have their association with macropores created by tree roots standing or decayed, which allow transmitting sub-surface flow downslope. The discharge rate of 321 springs, which were measured, varies from below 5 (32.3%), >5–50 (51.2%), >50–500 (13.4%) to above 50 (3.1%) l/min (figures 11 and 12).

3.2 Relation between parameters and likelihood (weight) of the groundwater spring occurrence

3.2.1 Topography

Topographic setting signifies the local and regional relief situation and gives an idea about the general direction of groundwater flow and its influence on groundwater recharge and discharge. Slope gradient, slope aspect, slope length, slope shape

Figure 11. Discharge of a measured spring 'Jor Dhara' at Kiwool.

and relative relief are important topographic parameters that affect the recharge and storage of groundwater. However, the physical properties of rocks and soil control the magnitude of recharge and discharge (Marklund and Wörman 2007). The variability of topographical features such as slope steepness, shape, aspect and relief, slope position

is reflected in variable water table configurations, which in turn depends upon the manner in which these features intersect with geological contacts, faults, joints, soil and other deposition characteristics (Higgins *et al.* 1985; Marklund and Wörman 2007; Younger 2007). The number, per cent and the calculated weight for the topographic parameter class are described in table 2.

Altitude and relative relief: Water tends to store at lower topography rather than the higher topography. The higher the elevation, the lesser is the groundwater potential and vice versa. Within the settlement limit of the study area, i.e., below snow or glaciers and/or barren rocky zone (<4000 m), the likelihood of the ground spring water as indicated by weight seems to decrease with increase in altitude, although the correlation is statistically not significant ($P < 0.05$) (table 1 and figure 13). Generally, the groundwater seepage zone increases as the altitude increases and the areas for gaining rainwater for infiltration progressively decrease with the decline in altitude. The weight of ground spring water was found to be higher in lower relative (or local) relief than the higher

Figure 12. Map showing the discharge rate of measured 321 springs at various locations.

Table 2. *Topography and groundwater springs.*

Altitude class (m)	No. of springs	No. class grids	% Springs	% Class grids	W_i^+	W_i^-	W
<1500	48	390	13.675	4.884	1.104	-0.101	1.129
1500–2000	130	1254	37.037	15.702	0.911	-0.301	1.136
2000–2500	136	1863	38.746	23.328	0.526	-0.23	0.681
2500–3000	33	1958	9.402	24.518	-0.998	0.196	-1.27
3000–3500	1	1786	0.285	22.364	-4.419	0.267	-4.762
3500–4000	3	735	0.855	9.204	-2.429	0.093	-2.599
Total	351	7986	100	100		-0.076	
Slope in degrees							
<5	7	122	1.994	1.527	0.281	-0.005	0.278
5–15	17	222	4.843	2.778	0.591	-0.022	0.605
15–25	86	1161	24.501	14.54	0.554	-0.129	0.675
25–35	138	2809	39.316	35.173	0.117	-0.069	0.178
35–45	84	2562	23.932	32.082	-0.305	0.119	-0.432
>45	19	1110	5.413	13.901	-0.971	0.099	-1.078
Total	351	7986	100	100		-0.008	
Relative relief (m/200 ² m)							
50	156	1913	44.321	23.953	0.655	-0.324	0.958
75	137	3486	39.058	43.655	-0.116	0.082	-0.219
100	58	2587	16.62	32.392	-0.689	0.22	-0.931
Total	351	7986	100	100	0	-0.021	
Slope shape							
Convex	99	2549	28.205	31.918	-0.129	0.056	-0.188
Straight	131	2584	37.322	32.357	0.15	-0.08	0.226
Concave	121	2853	34.473	35.725	-0.037	0.02	-0.061
Total	351	7986	100	100		-0.004	
Slope aspect							
Flat	1	58	0.285	0.726	-0.974	0.005	-0.968
N	40	562	11.396	7.032	0.5	-0.049	0.56
NE	32	955	9.117	11.962	-0.294	0.035	-0.318
E	62	1147	17.664	14.364	0.206	-0.039	0.256
SE	28	901	7.977	11.286	-0.372	0.04	-0.401
S	34	999	9.687	12.513	-0.278	0.035	-0.302
SW	54	1185	15.385	14.84	0.026	-0.005	0.041
W	56	1288	15.954	16.129	-0.023	0.004	-0.028
NW	44	890	12.536	11.149	0.111	-0.015	0.126
Total	351	7986	100	100		0.011	

Note: 1 grid = 200×200 m.

relative relief. This relation implies that less rugged topography and low relief allows for more space and time to percolate the rainwater and raise the groundwater to favourably provide the outlet for groundwater discharge. Such areas represent the subdued part of the topography where slopes are relatively gentle, as well as downslope, where the rock and colluvium aquifer reach the surface and seep out as spring. High internal relief indicates highly rugged and dissected topography made of runoff, erosion and incisions, which generally favours tapping and draining rainwater through

gullies and stream developed on the steeper slopes. High mountainous relief also promotes deep circulation of groundwater, denying access to groundwater outcrops (Forster and Smith 1988).

Slope gradient: Slope gradient regulates the amount and rate of runoff and water percolation into the subsurface and accumulates as groundwater storage. In the study area, the slope gradient indicates an inverse relation with the occurrence of groundwater spring. The likelihood of occurrence (weight) of the groundwater spring increases

Figure 13. Altitude map (digital elevation model) of the study area.

with decrease of slope gradient (figure 14) and the correlation is significant, i.e., $r^2 = 0.68$ ($P < 0.10$, $n = 6$). In general, the hydrogeologic landscapes with relatively steep terrain would not be expected to have an appreciable amount of groundwater recharge compared to runoff (e.g., Hudson and Anderson 2006). On very gentle slopes ($<5^\circ$), the surface runoff is slow, allowing more time for rainwater to percolate and is considered as good groundwater potential zone, whereas steeper slopes facilitate high runoff, allowing less residence time for rainwater hence comparatively less infiltration and poor groundwater potential (Florinsky 2000; Rao 2006).

Slope shape: Geomorphic significance of the shape of the slopes can be explained by its role in accumulating or dispersing the runoff. The concave slopes allow for the accumulation of runoff and deposition of colluvium, which strongly favours recharge as well as seepage as springs from hill-slopes (Younger 2007; Ghimire 2011). Whereas convex slopes, which are generally the upper segments of the slopes closer to the ridgeline, are runoff dispersal slopes that discourage the recharge of groundwater. The straight slopes in the study

area are generally steep footslope components produced by bedrock incision by fluvial processes induced by active tectonics (Lavé and Avouac 2001). The weight indicating the groundwater spring potential was found to be high on straight and concave slopes. The high frequency of the springs on straight slopes indicates the seepage of groundwater flow on a larger quantity from the downslope below the concave slopes, which acts as an intake of rainwater for groundwater recharge.

Slope aspect: Slope aspect reflects the moisture retention, vegetation and its relation to rain-bearing wind and attitude of rock bedding, which in turn influences the physical properties of slope material and soils and thereby the potential for groundwater. In the study area, the north, northeast and east facing slopes have the positive weight for groundwater potential (figure 15). The role of bedding structure and geology in relation to an aspect, and the slope aspect's role in moisture regime seem to have played a role in determining the groundwater spring potential. Although the south facing slopes in Nepal Himalayas receive more rainfall, they are steep due to geological

Figure 14. Slope gradient map of the study area.

Figure 15. Slope aspect map of the study area.

Table 3. *Drainage, flow accumulation zone and groundwater spring.*

Class	No. of springs	No. class grids	% Springs	% Class grids	W_i^+	W_i^-	W
Drainage density (km/km ²)							
<1.5	21	523	5.983	6.551	-2.127	0.636	0.059
2–2.5	145	1752	41.311	21.940	-0.415	0.449	1.958
3–3.5	146	2768	41.595	34.667	-0.458	0.535	1.829
3.5–4	33	2245	9.402	28.116	-1.840	0.797	0.185
4<	6	697	1.709	8.726	-3.003	0.405	-0.587
Total	351	7986	100	100		2.822	
Flow accumulation (no. of grids)							
>100	181	3580	51.57	44.795	0.148	-0.136	0.233
100	91	2132	25.93	26.677	-0.030	0.011	-0.092
50	51	1565	14.53	19.582	-0.310	0.064	-0.425
10	8	232	2.28	2.903	-0.252	0.007	-0.310
<10	20	483	5.70	6.044	-0.061	0.004	-0.117
Total	351	7992	100	100		-0.051	

Table 4. *Geology and groundwater spring.*

Unit	No. of springs	No. class grids	% Springs	% Class area	W_i^+	W_i^-	W
Geological units							
Pangang Formation	60	3516	17.094	44.032	-0.974	0.415	-1.412
Gyalthung Formation	68	709	19.373	8.884	0.835	-0.128	0.940
Shermathang Formation	196	3377	55.840	42.292	0.293	-0.278	0.548
Dhadkhola Formation	27	383	7.692	4.792	0.501	-0.032	0.511
Total	351	7986	100	100		-0.023	
Lineament density (km/km ²)							
0–0.72	41	1530	11.7	19.2	-0.512	0.093	-0.629
0.73–0.95	45	1618	12.8	20.3	-0.474	0.094	-0.591
0.96–1.18	62	1642	17.7	20.6	-0.158	0.038	-0.219
1.18–1.50	94	1647	26.8	20.6	0.275	-0.084	0.336
1.50–3.68	109	1549	31.1	19.4	0.499	-0.163	0.638
Total	351	7986	100	100		-0.023	

reasons with thin soil cover to promote higher runoff as well as because of high solar radiation, water in soil dries out faster than the north facing slopes. Hence, the south facing ridge slopes are usually dry and have low groundwater potential (Paudel and Vetaas 2014). It is acknowledged that in opposing slope aspects, the difference in soil, vegetation, water retention and infiltration rates is observed (Higgins *et al.* 1985; Younger 2007).

3.2.2 Drainage density and flow accumulation

Drainage density points to rock permeability and infiltration capacity and therefore recharge capacity. It indicates the rate that precipitation infiltrated compared to surface runoff where rocks

are highly permeable, infiltration to groundwater is high and less water is transported in rivers as surface water and vice versa. Low drainage density is, therefore, related to higher recharge and higher groundwater potential (Murthy 2000; Thangarajan 2007; Magesh *et al.* 2012). However, our study does not reveal such relation. No definite association between the occurrence of groundwater spring and drainage density is observed (table 3). Because all the geological units of the area are made of high-grade metamorphic rocks whose permeability does not vary significantly; therefore, the drainage density seems to be controlled by localised factors. Groundwater recharge and discharge are mostly through rock discontinuities. Many of drainage lines are controlled by joints and faults.

Figure 16. Flow accumulation map of the study area.

Table 5. Land use and vegetation index, and ground spring water.

Class	No. of springs	No. class grids	% LS	% Class area	W_i^+	W_i^-	W
Land use							
Barren	3	147	0.85	1.84	−0.790	0.010	−0.823
Forest	189	1086	53.85	13.60	1.523	−0.648	2.149
Cultivation	33	4204	9.402	52.64	−1.76	0.692	−2.473
Cut and cliff	0	158	0.000	1.98	−11.51	0.021	−11.55
Grass	126	2314	35.90	28.97	0.225	−0.107	0.310
Others	0	78	0.000	0.976	−11.513	0.010	−11.54
Total	351	7986	100.00	100.00		−0.022	
Normalised difference vegetation index							
<0	2	245	0.489	3.069	−1.875	0.027	−1.983
0–0.2	6	1010	1.711	12.641	−2.039	0.124	−2.243
0.2–0.4	82	2040	23.472	25.545	−0.088	0.029	−0.198
0.4–0.5	159	2398	45.232	30.030	0.433	−0.255	0.607
0.5–0.6	102	2293	29.095	28.715	0.014	−0.006	−0.061
Total	351		100.00	100.00		−0.081	

Flow accumulation or upslope contributing area: Flow accumulation or upslope contributing area refers to upslope area drained from a location in topographic position. The flow accumulation, which is calculated from the DEM, can be a proxy expression of a ridgeline, sites of residual soil, colluvium concentration, and moisture

availability and drainage flow line (Beven and Kirkby 1979; Dietrich *et al.* 1995; Pack *et al.* 1999). Flow accumulation determines where the slope materials and rainwater are dispersed and where the flow of both water and slope materials tend to concentrate. The former is the divergent slopes and the later one is known as the

Figure 17. Land cover map of the study area.

convergent slope, which are potential areas for colluvium and saturation and recharge and seepage zone. The present study shows that the weight of occurrence of groundwater spring is high on locations, which receives the accumulation of water and sediment from the larger areas (figure 15). The flow accumulation zones and high discharge of springs in the study area are closely associated with the accumulation of hillslope deposits underlain by highly weathered or fractured rocks, which facilitate to transmit recharged water flow through the sub-surface to surface (Winter 1998).

3.2.3 Geology and lineaments

Geology controls occurrence, movement and storage of groundwater. The petrography, stratigraphy, structure, lithology and thickness of a given rock type control the porosity and permeability, which define the storage capacity of an aquifer (Higgins *et al.* 1985; Winter 1998; Crawford and Kath 2005; Chinnasamy and Prathapar 2016). The shape, sorting and packing of grains in the rocks during their formation determine primary porosity. Secondary porosity, such as joints, fractures and solution opening, is formed after the rock has

been deposited. The number and arrangement of fracture openings and the degree to which they are filled with fine-grained material control secondary porosity. The geological map (figure 2) shows the rock stratigraphy and lithology in different geological units as the wells major thrust, faults and lineaments, which contribute to varying hydraulic conductivity and permeability for occurrence, movement and storage of groundwater.

The weight of occurrence of ground spring water was found to be high in the Gyalthung, Sermathang, Dhadkhola Formation (table 4 and figure 16). Highly sheared and fractured rocks of gneiss, schist and quartzite beneath the soil and saprolite in these geological unit favour high infiltration rate and groundwater storage, which yield to discharge of ground spring water (Kerrich 1986; Florinsky 2000). Geological contacts, faults, joints, soil and other deposition characteristics (Higgins *et al.* 1985; Marklund and Wörmann 2007; Younger 2007) intersecting the topographic features control the recharge and discharge of groundwater.

The presence of lineaments influences the potentiality of groundwater occurrence in the crystalline hard rock (Nag 2005; Kolawole *et al.* 2016). These lineaments in the study area generally

Figure 18. Groundwater spring potential zone.

represent the major joints and faults in the tectonically active areas, where the bedrocks are intensely deformed (Dhital *et al.* 2002; Dhital 2015). Hence, these lineaments act as a conduit for groundwater movement, which result in increased secondary porosity and therefore, can serve as the groundwater potential zone. In the study area, the lineaments were identified from Landsat-8 imagery and their line density was calculated, the weight of the groundwater spring occurrence strongly correlated with lineament density, i.e., $r^2 = 0.94$ ($P < 0.01$, $n = 5$). This strongly supports the role of rock discontinuities in high-grade metamorphic rocks as groundwater aquifer and a conduit for both recharge and discharge of groundwater.

3.2.4 Land use and vegetation density

Land use is an important characteristic of the runoff process that affects the infiltration, erosion and evapotranspiration. Groundwater spring is well connected with the landscape and land use that it lies beneath. Land use affects the

groundwater resources through changes in recharge and by changing demands for water (Lerner and Harris 2009; Prabhakar and Tiwari 2015). The weight of occurrence of ground spring water was found to be high in the forest areas and low in the barren areas (table 5 and figure 17). The normalised difference vegetation density index map also reveals the significant positive correlation (i.e., $r^2 = 0.73$; $P < 0.10$, $n = 5$) between the vegetation density and the groundwater spring occurrence. Dense vegetation in the study area lies in plane concave or flow accumulating slopes, where soils and colluvium deposits are deep and relatively moist to favour the vegetation growth as well as for high groundwater recharge to raise the groundwater level to the point where water issues as spring from the ground. It is recognised that forested land decreases the amount and velocity of storm runoff over the land surface. This, in turn, increases the amount of water that percolates into the ground, a portion of which can ultimately recharge underlying aquifers, which transmit groundwater flow to the surface as springs (Spears 1982; Myers

Figure 19. Predictive and success rate of groundwater spring potential zone.

1983; Bartarya 1989). Such spring flows, which feed streams and wetlands, help to maintain their water levels during dry periods. However, several studies suggest that forest may not be the best land cover to maximise water yield, regulate seasonal flows and ensure high water quality (summarised by Gilmour *et al.* 1987; Bruijnzeel 2004; Calder 2007; van Dijk *et al.* 2007; Ghimire *et al.* 2012). One evidence reveals that afforestation will increase interceptions typically, reduce local average water yield as well as low flows due to lower infiltration (Bruijnzeel 2004). The net effect of land

cover on water yield will, however, depend on the characteristics of a given hydrogeologic landscape – such as its bedrock geology and structure, surficial geology, soil type and topography (Smerdon *et al.* 2009).

3.2.5 Groundwater spring potential map

As stated earlier 11-factor maps were overlaid with the help of ArcGIS9.3 to get groundwater spring potential zone (max value 4.81; min value −24.25; mean −1.14; standard deviation 2.87) as shown in

the figure. The total weighted map was classified into four classes corresponding to very low potential, low potential, moderate potential and high potential (figure 18). The classification was based on the Jenks natural break on the histogram of index values on the continuous groundwater spring potential raster map.

3.2.6 Prediction and success rate of groundwater spring potential zone and validation

Validation was performed by comparison with all surveyed groundwater spring location data, using a prediction rate and success rate curves (figure 19). The prediction rate illustrates how well the estimation performs with respect to the spring locations used for constructing the groundwater spring potential zone map. Similarly, the success rate refers to how well the survey springs water locations that were not included for analyses conform to the estimated potential zones of groundwater spring. Fifty out of total surveyed springs were randomly not included in the analysis.

The predictive rate indicates that with a decrease in the index of groundwater spring potential, the occurrence of all surveyed groundwater spring progressively declines. Similarly, the success rate reveals that with a decrease in the index of groundwater potential, the occurrence of surveyed groundwater spring randomly not included, also progressively declines. In order to evaluate the prediction and the success rate of groundwater spring locations, area under the curve was estimated (figure 19). The area under the curve shows the prediction and success rate of 81.4% and 80% for the model, respectively. This indicates that the WoE model mapping for groundwater spring potential is valid and could be replicated elsewhere, where the data of groundwater from the hydrogeological survey is not available.

4. Summary and conclusions

The study has assessed the groundwater spring potential by applying GIS, which integrated and analysed the data obtained from the GPS survey, maps and satellite imageries in this part of the Himalaya. A spring GPS inventory map showing 412 groundwater spring locations was prepared from the field survey. These groundwater springs were mainly originated from the weathered-jointed

or fractured rock aquifers in the high-grade metamorphosed rocks.

The analysis of association of these springs with *in situ* factors such as altitude, slope gradient, relative relief, slope shape, slope aspect, drainage density, flow accumulation, geology and lineaments, land use, and vegetation density was done through calculating weights, applying on WoE model. The weight indicated the likelihood of ground spring water occurrence in multiple classes of each factor.

Gentle slope class, low relative relief, high flow accumulation, north- and east-facing slopes, denser lineament density, altitude class of 1500–2500 m, high vegetation density and forest demonstrated a higher likelihood of spring occurrence. The likelihood of occurrence was found to be very strong in areas of dense lineaments. Combining the weight maps of each of the chosen factors, potential groundwater spring map was produced, and validation of the map was successful.

The result indicates the WoE method of predicting groundwater potential could be replicated in a similar biophysical environment, where a hydrogeological or geophysical survey of groundwater has not been done. Nevertheless, the limitation of this statistical model is that it relies on the association of groundwater spring with casual *in situ* factors that are chosen without necessarily understanding the process and mechanism of the groundwater interaction with them. This limitation does not, however, undermine the importance of groundwater spring potential map in devising a strategy and programme for the conservation of spring seepage zones and a scientific evidence for planners, policy makers and managers in water resource management, land use planning and building climate resilience.

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