

Improving water resources management using participatory monitoring in a remote mountainous region of Nepal

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ABSTRACT

Study Region: We interrogate the water resources of the Upper Kaligandaki River Basin (UKGRB), in the remote Mustang District of northwestern Nepal. The Nepal Himalayas are a major reservoir of freshwater; yet the impediments to its exploitation by local inhabitants are manifold, including weak governance structures, steep and irregular terrain, and frequent natural hazards that are linked to climate change. The UKGRB is characterised by its extreme fragility, paucity of water and water-related data, and enormous variability of the effects of climate change on glaciers through time and space.

Study Focus: The purpose of this paper is to elucidate catchment hydrology and local flow variability, before demonstrating the ways in which sustainable water resource management (WRM) can be achieved regionally.

New Hydrological Insights for the Region: We present the local crop water balance, and suggest methods to reduce crop water requirements and to ensure a more equitable distribution of available seasonal flow. We also propose a series of long-term changes that are needed to secure sustainability. Then, we suggest that the principles of citizen science can help to improve the spatial coverage of data, generating new hydrological time series (e.g. river discharge), which can aid local decision makers in the WRM realm (e.g. irrigation scheduling). This approach has the potential to be scaled-up across the entire UKGRB (and, indeed, Nepal as a whole).

1. Introduction

1.1. Water security and data scarcity in the Himalayas

Mountains contribute a meaningful proportion of the world's freshwater supply (32% of global discharge: [Meybeck et al., 2001](#)). The Hindu Kush Himalayas (HKH), also known as the 'water towers of Asia' ([Mukherji et al., 2015](#)), contribute to agriculture and food security across South Asia ([Rasul, 2014](#)). However, the complex physiography and microclimatic variability in the Himalayas result in a strong spatial and temporal variation in water flow ([Pandey, 2016](#)). More than 80% of the precipitation in Nepal falls within four months of the year; much of this volume accumulates during few extremely intense rainfall events ([Klatzel and Murray, 2009](#)). The

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issue of an excess or paucity of water across the Himalayas is therefore a long-standing problem that has continuously impeded effective water resource management (WRM) in the region (Bandyopadhyay and Gyawali, 1994).

Climate change has increased the temporal and spatial uncertainty in mountain water availability (e.g. Viviroli et al., 2007; Ragettli et al., 2016). Spatial variation in the rate of warming and precipitation dynamics has already been reported within the Himalaya (Immerzeel et al., 2010; Pandey, 2016). Any potential changes in temperature and precipitation adversely affect melt characteristics of glaciers (e.g. Harper and Humphrey, 2003; Kääb et al., 2012; Pritchard, 2017). Therefore, regions dominated by snowmelt hydrology are highly susceptible to climate change, since river flow regimes are known to have been significantly altered in terms of seasonality and intensity (Neupane et al., 2014). Such fragile regions constitute, at a local level, remote villages and settlements situated at higher elevations (Mukherji et al., 2015) that are strongly reliant on ecosystem services (Buytaert et al., 2014). Likely changes in the local precipitation and snow cover patterns will in turn affect the timing and volume of river discharge from these mountainous regions.

Coupled with the high susceptibility to changing environmental dynamics, remote mountainous regions also face a severe scarcity of hydrometeorological data, thereby limiting an understanding of local hydrological processes, and impeding efficient WRM of the region. This is partly because government agencies tend to give high-elevation sites a lower priority because of costs and logistical issues (Karpouzoglou et al., 2016). In Nepal, 80% of hydrological stations installed by the Department of Hydrology and Meteorology (DHM) are situated at low altitude (< 500 m) and only measure the discharge of principal rivers. Yet, due to the strong annual variation in river flow, the dangers they pose, and the amount of sediment they carry during the Monsoon, they are rarely used by mountain people for water supply and irrigation, who use smaller streams instead (Smadja et al., 2015). As a direct result, small settlements are generally situated at high elevations beyond the reach of any national-scale intervention of WRM and planning. With very little information about the local hydrology and individual water balances, mountain communities rely heavily on their indigenous knowledge to manage the available water resources.

Location-specific interventions are required to understand local water issues faced by mountain communities here. Moreover, socio-ecological interactions in mountain systems vary both across and within the region. Such complexities, the degree of particular uncertainty, and unpredictable interactions, require a more bottom-up, inclusive approach, the shared knowledge base of which lends aligns closely with the principles of polycentric governance of ecosystem services (Buytaert et al., 2014; Paul et al., 2018).

1.2. Citizen science for knowledge co-generation

Citizen science has been recognised as a way to include stakeholders and the general public in the planning and management of local ecosystems (Conrad and Hilchey, 2011; Buytaert et al., 2014; Paul et al., 2018). Underpinned by a bottom-up, participatory approach, the philosophy of citizen science lies in a transformative or community-based monitoring and management model (Conrad and Hilchey, 2011), where the non-scientist is involved in every stage of the monitoring program, from the initial problem identification to the communication and implementation of the results, therefore supporting local decision making (Paul et al., 2018).

The ubiquity of citizen science applications has already been noted in fields as diverse as ecology and population studies (Buytaert et al., 2014); in contrast, the uptake of citizen science in hydrology has hitherto been rather slow (Buytaert et al., 2016). In this sense the scope is limited to water quality monitoring, primarily occurring in developed countries, i.e. a clear geographical bias (Buytaert et al., 2014). So far, the potential of citizen science has mostly been analysed from the social perspective of increasing local awareness and scientific literacy. Its capability to manage water resources and enhance the wellbeing of remote mountain communities of developing regions is still largely unexplored. Mainly due to the underlying complexities in hydrological data collection for prolonged periods, the need for continued local interest and objectivity regardless of long-term perspectives and complex management structures, the use of citizen science to generate locally relevant actionable knowledge for WRM has been largely constrained (Buytaert et al., 2014, 2016). Furthermore, the data generated by citizen science may be fragmentary and of low quality, which could pose a major challenge for water scientists in terms of information feedback to local communities in a less technical and more easily understandable form, with the possibility of generating a permanent misunderstanding (Buytaert et al., 2014).

The recent advent of low-cost, robust environmental sensors has the ability to be harnessed by citizen science applications in WRM (Buytaert et al., 2016; Paul et al., 2018). The ability to employ such sensors in large quantities may provide valuable information for areas where the spatial variation of a particular hydrological variable (e.g. precipitation or discharge) is high or of particular importance (Buytaert et al., 2012). Such a high spatial coverage network could ideally complement official hydrometric networks operated by national meteorological offices, which focus on long time series (Buytaert et al., 2016).

1.3. Objectives

The objectives of this study are twofold: first, we attempt to understand catchment hydrology and water flow variability in the data-scarce study area. Secondly, using knowledge of crop water modelling and a water balance modelling approach, we deduce locally relevant solutions for sustainable irrigation practices and potential pathways to scale up this approach of better water sharing across hydrological and/or administrative boundaries for regional WRM. The remainder of this paper is structured as follows: in Section 2, we briefly describe the hydrological characteristics of the study area. In Sections 3 and 4, we discuss the water resources assessment using the data generated by participatory monitoring of stream flow and rainfall in local communities of the Mustang Valley, Upper Kaligandaki Basin, Nepal. A simple water balance is then applied to determine the irrigation schedule for effective water allocation among farmers; and possible water management options for local decision making are then suggested. Also in this section, potential entry points and pathways to scale up such local initiatives for national WRM are discussed. Section 6 offers

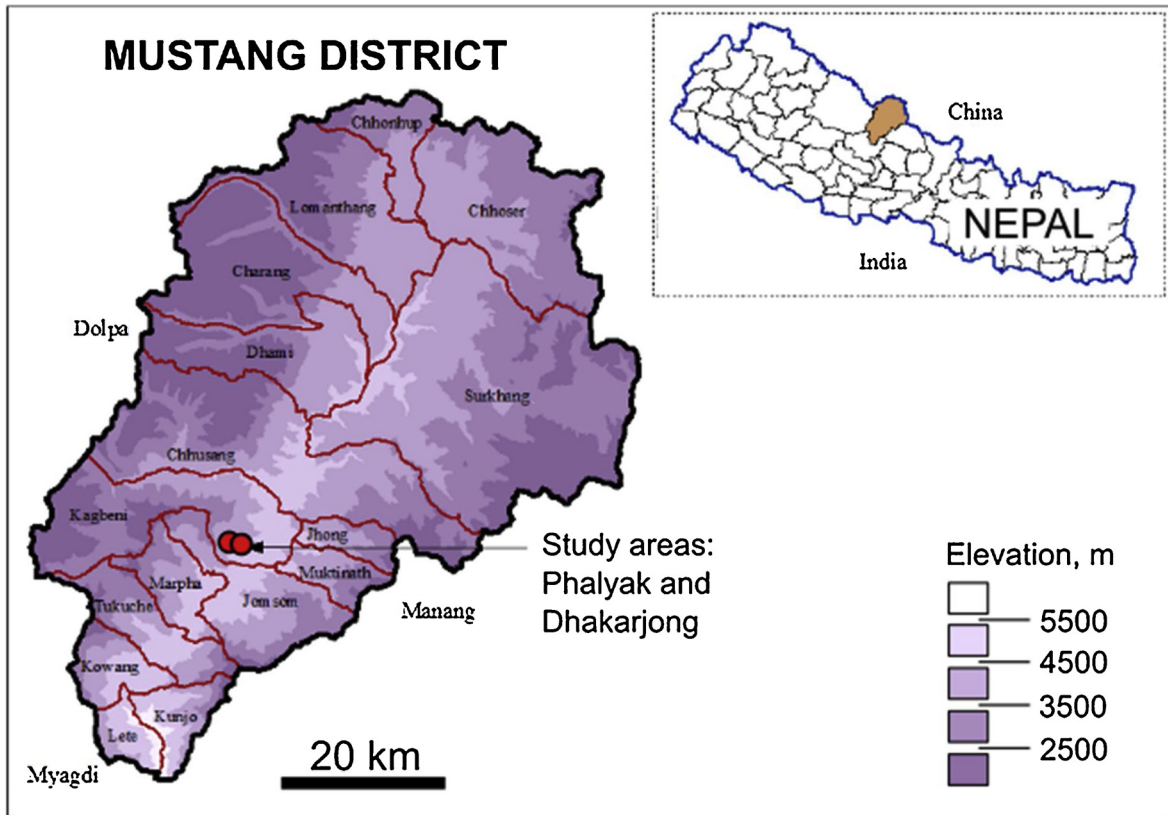


Fig. 1. Location map of the study area.

conclusions and a brief future outlook.

2. Study region

The study is specifically focused on two mountain villages: Dakarjong and Phalyak, located in the Kagbeni Village Development Committee of the Mustang District, one of the northernmost districts of Western Nepal bordered by the Tibet Autonomous Region of China to the north (Fig. 1). The Kaligandaki River runs through the district, carving the deepest gorge between the two high mountains of Annapurna and Dhaulagiri (Basnet, 2007). Both study villages lie within the Upper Kaligandaki River Basin (UKGRB) at an altitude of ~3200 m, contributing to the watersheds of the snow-fed Lumbuk stream, a Kaligandaki River tributary. Comprising 2567 ha, Dhakarjong consists of 33 households of 191 residents, while Phalyak comprises 48 households and 249 people within an area of 6562 ha (Regmi and Gurung, 2005). These villages lie just 2.5 h from the district headquarters of Jomsom but do not lie on the famous Annapurna trekking circuit; agriculture and subsistence farming therefore remain the dominant livelihood strategy here. Naked wheat, wheat, buckwheat (sweet and bitter), peas and pulses are the major cereal crops (farmers also cultivate other vegetables, but only in very small areas).

In recent years, this region has seen a decrease in snowfall during winter and accelerated snow melt in summer, resulting in increased hydrological extremes across the basin (Manandhar et al., 2012; Chapagain and Bhusal, 2013; Pandey, 2016), a trend that is expected to intensify in the coming decades (e.g., Ragetti et al., 2016). Thus water availability and access have involved highly contested ecosystem services (ESS) between individuals, communities, and social groups across most villages of UKGRB (Basnet, 2007; Chapagain and Bhusal, 2013). Water allocation between individual households is based on either water share or landholding size (Basnet, 2007).

3. Materials and methods

3.1. Hydrometeorological stations

There are 10 meteorological stations in Mustang that record daily precipitation and maximum and minimum temperatures across the region (Fig. 2), all operated by DHM. There is only one monitoring station installed on the Kaligandaki River in the village of Syang, downstream of Jomsom. Only the meteorological station at Jomsom offers continuous and reliable climate and precipitation datasets. Both study villages lack hydrometeorological stations, resulting in knowledge gaps of the volume of flowing water and its

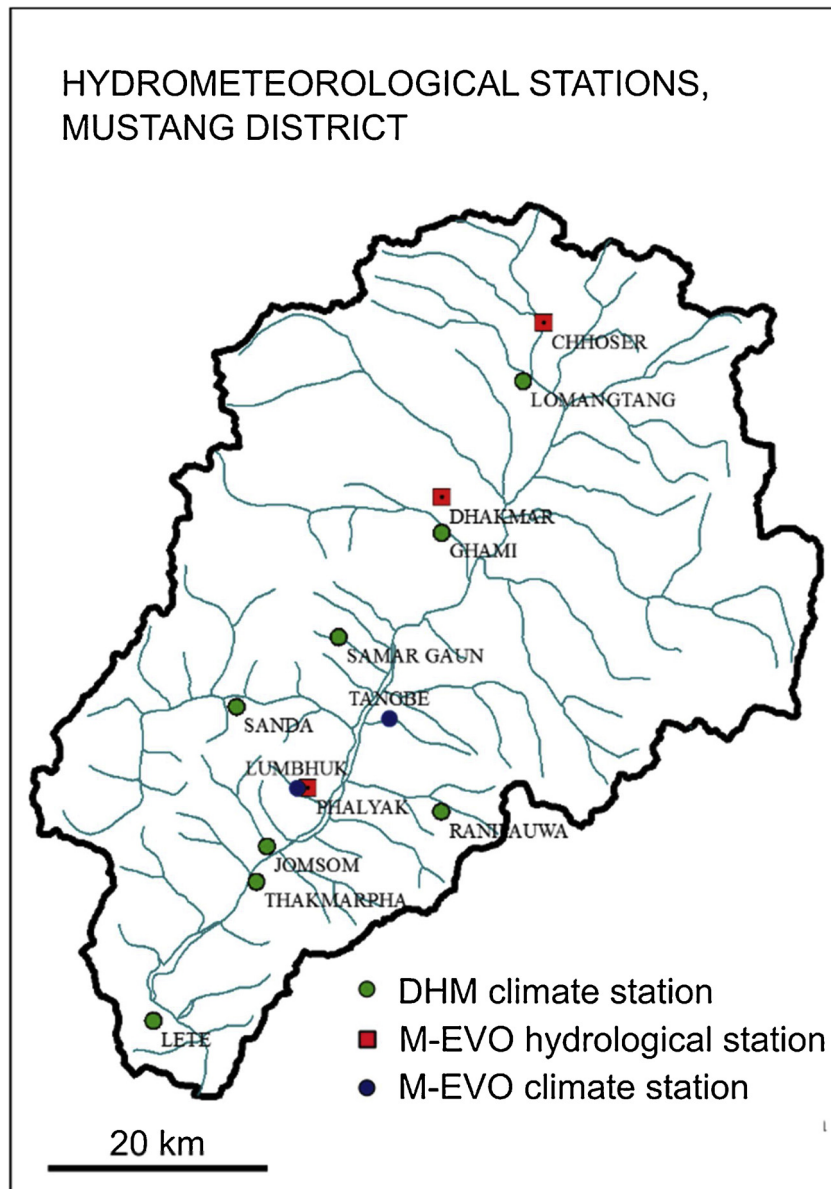


Fig. 2. Distribution of hydrometeorological stations in the Mustang District, northwestern Nepal.

variability on an annual basis.

First, monitoring instruments consisting of automatic water pressure level sensors and staff gauges were set up at Lumbuk Khola (Fig. 2). Also, rain gauges (automatic and manual) were installed in Dakarjong. Local people were informed of, and trained about the operation of, the monitoring instruments, the method of data collection, and its use in local water sharing and allocation.

The entire installation process of monitoring stations was participatory; the locals showed interest in monitoring water flow and rainfall, as well as maintaining the station. Periodic measurement of discharge using a current meter was also undertaken to establish a rating curve and to quantify the volume of water of the Lumbuk Khola and its variability throughout the year.

3.2. Data analysis and modelling

We exploit one year's worth (July 2015 – July 2016) of river flow data from the Lumbuk gauging station to quantify the volume of water and its variability across the cropping season. Also, by using temperature data from the Jomsom station, the crop water needs in Dakarjong and Phalyak are estimated. Based on a simple water balance approach, existing cropping practices are then analysed, in this way obtaining a potential solution for an efficient irrigation system.

Table 1

Cropping calendar for major crops grown in the study area (after Regmi and Gurung, 2015).

	Major Crops	Months			Growing period (months)	Irrigation frequency (if water available)
		Seeding	Start of irrigation	Harvest-ing		
Winter crops	Naked wheat ^a	Nov/Dec	Apr/May	Jun/Jul	6.5	4/5
	Wheat ^b			Jul/Aug	6	4/5
	Barley			Jun/Jul	5	4/5
Summer crops	Buckwheat (sweet)	Jun/Jul	Aug/Sep	Sep/Oct	4	4
	Buckwheat (bitter) ^c			Mid Sep-Mid Nov	3.5	4
	Maize				4	3
	Potato			Sep/Oct	4	–
	Beans and pulses			Aug/Sep	3	–

^a If no snowfall, irrigation starts from mid-December to mid-April.^b Harvest is 10–15 days ahead of naked wheat.^c Harvest is 10–15 days ahead of sweet buckwheat.

3.2.1. Hydrological regime analysis

A hydrological analysis was carried out with a view towards developing a supply-demand relationship for improved water allocation and equitable sharing between local farmers. Stream discharge is the most important parameter for understanding catchment hydrology. We therefore transformed daily average stage data to daily discharge. A rating curve was built to evaluate the water resource potential of the Lumbuk stream. Altogether, six measurements were carried out during the study period, based on which the rating curve was calibrated. Any possible backwater effect and unsteadiness in the flow are neglected in this case. The general rating curve equation is usually in power form as follows (Kennedy, 1984; Herschy, 1995):

$$Q = C(h + a)^\alpha \quad (1)$$

where Q is discharge in $\text{m}^3 \text{s}^{-1}$, h is river stage in m, and C , a and α are calibration coefficients. A stream flow hydrograph for the entire one-year period allowed us to derive the temporal distribution and variation of streamflows.

Baseflow separation is particularly important in this hydrological analysis because the study stream is snow-fed; thus, stream discharge is expected to have a significant component of baseflow. Monsoon rain contributes very little to irrigation here: rather, the farming system is much more dependent on meltwater for irrigation. Thus it is more convenient to consider the available baseflow as a further basis for developing irrigation management strategies.

3.2.2. Crop water models and irrigation scheduling

In most villages of the Upper Mustang, altitudinal constraints and water access issues limit the cropping season to one crop per year. However, in settlements located at lower elevations (i.e. most villages in the Lower Mustang), two crops are grown in a year (Su et al., 2013). The cropping calendar for the major crops grown in Dakarjong and Phalyak is provided in Table 1.

Temperature data were corrected for elevation using Eq. (2); the Lete station, being in a different climatic zone, was excluded from regression analysis. Therefore, the data from the other three stations were employed to calculate monthly lapse rates for maximum and minimum temperatures using Eq. (2):

$$T = C + LRE \quad (2)$$

Where T (temperature in $^\circ\text{C}$) is a dependent variable, C is the constant for temperature at zero elevation, E is elevation in km and the coefficient LR is the temperature Lapse Rate in $^\circ\text{C km}^{-1}$. Table 2 presents the calculated values of monthly lapse rate for temperature maxima and minima of Mustang District. Using the calibrated values of monthly lapse rate, the daily maximum and minimum temperatures for the study area were extrapolated and adjusted from the Jomsom Station data.

One major objective of this study is to develop a demand-based crop-water model and to estimate the water requirement of local crops in the study villages. This requires the computation of reference evapotranspiration (ET_0) beforehand. Since the only available climate data for the region were air temperature, a temperature-based formula (Hargreaves and Samai, 1985) was used to compute reference evapotranspiration. Considering the paucity of available weather data, Eq. (3) is considered to be the most reliable alternative to estimate the ET_0 rates (Allen et al., 1998):

$$ET_0 = 0.0023(T_{\text{mean}} + 17.8)(T_{\text{max}} - T_{\text{min}})^{0.5}R_a \quad (3)$$

Where, T_{max} , T_{min} and T_{mean} are the maximum, minimum and mean air temperature in $^\circ\text{C}$, respectively; R_a is the solar insolation in mm day^{-1} , which depends on latitude and the time of the year, and can be estimated using the procedures outlined in Allen et al. (1998). Eq. (3) is likely to underestimate ET_0 due to the exclusion of aerodynamic variables that are, in fact, paramount in determining evapotranspiration in arid regions (Garcia et al., 2004). Therefore, the use of extremes rather than the mean is usually recommended for these kinds of areas (Thomas, 2008). From the linearly extrapolated maximum and minimum temperature based on the simple lapse rate equation, ET_0 for the study area was estimated on a daily basis, and then aggregated to obtain monthly and seasonal estimates. The single crop coefficient approach (i.e. $ET_c = K_c ET_0$) was employed to estimate the potential (maximum)

Table 2

Monthly lapse rate for maximum and minimum temperatures in the Mustang District.

Months	Maximum temperature			Minimum temperature		
	C _m (°C)	LR _m (°C/km)	R ²	C _n (°C)	LR _n (°C/km)	R ²
Jan	23.9	−4.60	0.98	13.69	−5.87	0.97
Feb	26.1	−4.94	0.99	15.43	−6.03	0.98
Mar	26.0	−3.79	1.00	16.12	−5.34	0.98
Apr	25.4	−2.58	0.99	15.78	−4.29	0.98
May	24.6	−1.52	0.93	16.08	−3.30	0.94
Jun	27.0	−1.67	0.92	19.79	−3.15	0.92
Jul	26.1	−1.33	0.95	22.38	−3.33	0.90
Aug	27.0	−1.66	0.97	21.86	−3.31	0.87
Sep	26.1	−1.74	0.99	19.51	−3.31	0.88
Oct	25.4	−2.68	1.00	14.89	−3.79	0.93
Nov	22.9	−2.72	0.97	11.80	−4.05	0.95
Dec	24.4	−3.98	0.98	10.04	−4.41	0.96

C_m = maximum constant temperature at zero elevation.C_n = minimum constant temperature at zero elevation.LR_m = lapse rate of maximum temperature.LR_n = lapse rate of minimum temperature.

evapotranspiration (ET_c) of the crops. The crop growth periods and adopted coefficient values for local crops for this study are listed in Table 1.

Since the study area is an arid zone and high winds prevail throughout the year, the K_c values for the mid-season tend to be higher in such climatic conditions (Allen et al., 1998). For climate data that differ from minimum relative humidity (RH_{min}) of 45% and wind speed (u₂) other than 2 ms^{−1}, the K_c values (K_{c,mid} and K_{c,late}) provided in Table 1 were adjusted per Eq. (4) given by (Allen et al., 1998):

$$K_c = K_{c(Table)} + [0.04(u_2 - 2) - 0.004(RH_{min} - 45)]\left(\frac{h}{3}\right)^{0.3} \quad (4)$$

The observed minimum relative humidity data at the Jomsom station (Department of Hydrology and Mines (DHM), 2015) and simulated monthly wind speed data averaged over four seasons were used for this adjustment. A general procedure for developing the crop water model and estimating ET_c is shown in Fig. 3.

In actual field conditions, the soil moisture available in the root zone hardly allows plants to sustain ET_c; rather, a fraction of it, depending on the soil moisture availability, is lost as evapotranspiration. This is known as the Actual Evapotranspiration (ET_a), which can be calculated from the combined effect of K_c and a soil water stress coefficient (K_s) as follows:

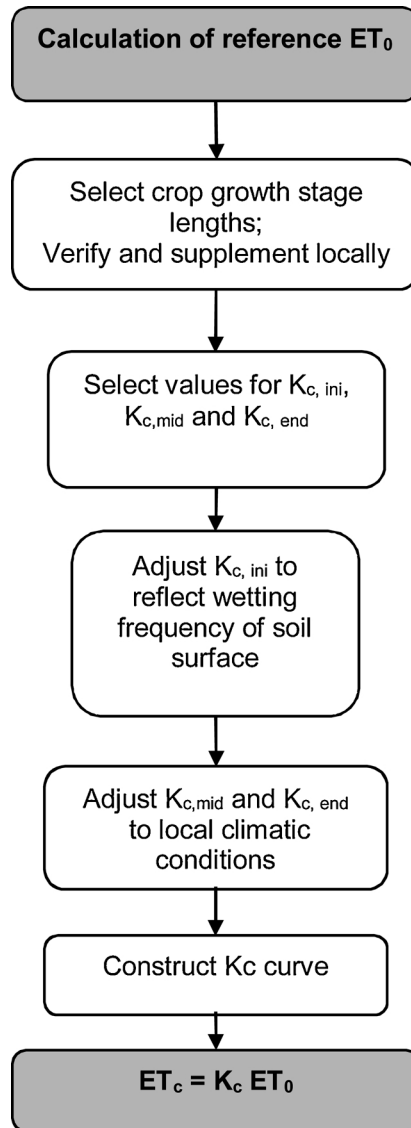
$$ET_a = K_s K_c ET_0 \quad (5)$$

The estimation of K_s and the actual evapotranspiration (ET_a) requires the further computation of a daily soil water balance in the root zone. For this purpose, a soil water balance model, WaSim (Hess and Counsell, 2000), was used. WaSim is a one-dimensional physically based water balance model that estimates daily soil water storage based on water influxes (viz. rainfall and irrigation) and outfluxes (i.e. evapotranspiration and drainage: Hess and Counsell, 2000). This model was chosen due to its simplicity, computational scale on a daily basis, and ability to capture hydrological processes in the root zone. The initial soil moisture was assumed to be at field capacity, which is normally adopted for initiating soil water balances (Allen et al., 1998). As per the local cropping calendar, the crop planting date also happens to coincide with either the rainfall or snowfall period, so it is plausible to assume a field capacity state of soil at the start of the cropping season.

The current cropping system (Table 1) and existing irrigation application (i.e. fixed amount and fixed interval) in response to the seasonal water availability were first evaluated to assess the impact of the existing water management scenario on the water balance of the catchment. The same cropping pattern was then analysed for an optimum water management scenario (i.e. irrigation to sustain actual evapotranspiration fully). The water requirement in field (WRF) for the existing mixed cropping pattern in these remote villages was then calculated for each month of the year. By incorporating the losses during water delivery, application, field application, potential seepage and evaporation from canals and ponds, the total water required for withdrawal (WRW) was estimated. Eq. (6) gives the relationship between WRF and WRW:

$$WRF = e_c e_a WRW, \quad (6)$$

where e_c is the conveyance efficiency and e_a is the application efficiency of the irrigation system. The potential area for agriculture can then be calculated by comparing the gross water demand per unit area to the actual volume of water available in the stream. Finally, different irrigation scenarios based on cropping management and irrigation techniques were explored to identify the best possible water management arrangement, subject to the given natural limitations of water.

Fig. 3. Procedure to estimate ET_c .

4. Results and discussion

4.1. Water availability

The rating curve developed for the Lumbuk stream is $Q = 13.53(H - 0.001)^{3.418}$. This is shown in Fig. 4. The daily hydrograph estimated from the rating curve is illustrated in Fig. 5. The average discharge in the stream is 36 Ls^{-1} . A minimum discharge of 19 Ls^{-1} and maximum of 196 Ls^{-1} are observed in June and July, respectively. This kind of river behaviour, and average discharge values, is common in this region of Nepal, as the summer Monsoon brings more than 80% of annual runoff to the river. A corollary that can be seen in Fig. 5 is that the range of discharge values (and interannual variability) is high and depends on the Monsoon strength for each year. However, the Monsoon in this Trans-Himalayan region is attributed to westerly disturbances that occur in a bimodal fashion, peaking in May and December. A somewhat similar pattern can also be seen here; however, the peak observed in March/April is not pronounced.

The behaviour of the hydrograph cannot be directly correlated with rainfall events; rather, it is governed by snowmelt. A simple water balance of the UKGRB by Chapagain and Bhusal (2013) highlighted the significant contribution of snowmelt and groundwater to annual runoff of the Kaligandaki River, particularly in the summer Monsoon season. Thus, such a large streamflow in summer could be more likely due to the accelerated melting of ice in the Lumbuk watershed because of the elevated temperatures. Soon after summer, a distinct recession curve followed by a stable and roughly constant flow is observed (Fig. 5).

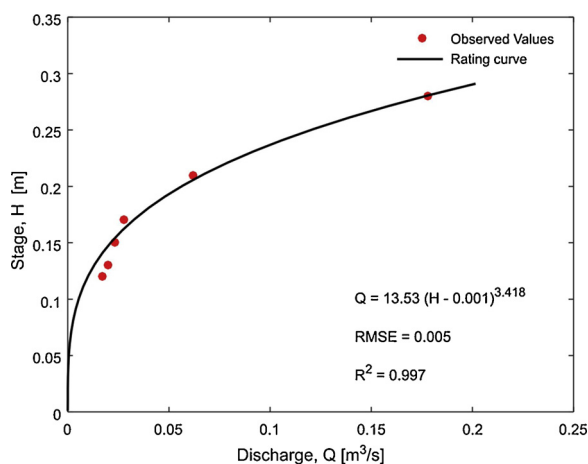


Fig. 4. Rating curve for Lumbuk stream.

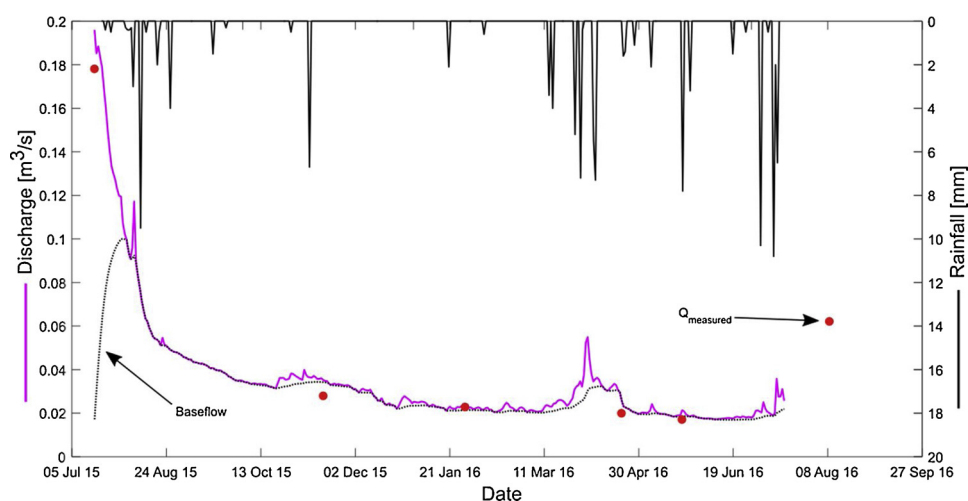


Fig. 5. Hydrograph of Lumbuk stream, showing the contribution of baseflow.

Baseflow estimated from the Boughton two parameter algorithm (Chapman, 1999) also reflects the characteristics of this mountainous stream. As shown in Fig. 6, baseflow is dominant for more than 80% of the year. For the remaining 20%, baseflow is almost half streamflow. Thus, taking baseflow for the water resource assessment does not seem to underestimate the flow in the

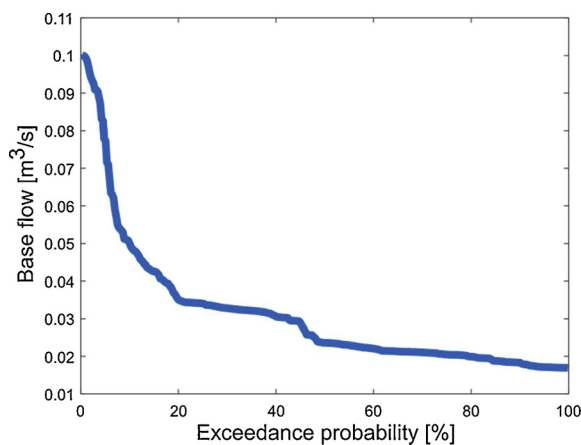


Fig. 6. Baseflow duration curve, Lumbuk stream.

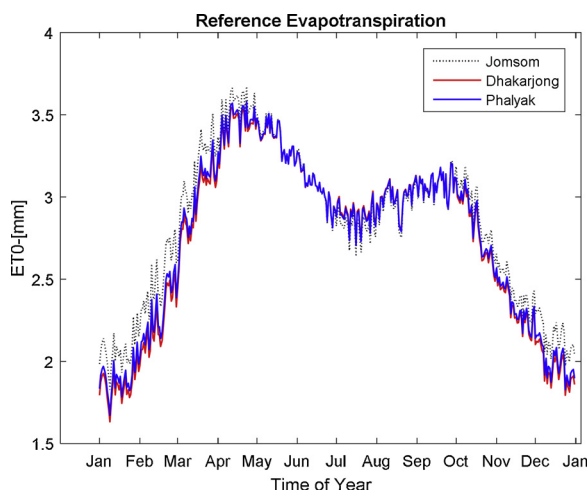


Fig. 7. Annual reference evapotranspiration (ET_0) for the study area.

stream, but rather can provide a sustainable solution. The monthly availability of water from the Lumbuk stream is therefore calculated from baseflow (Fig. 6). The annual runoff in the stream is estimated to be 0.99 Mm^3 , with low flow in winter and the pre-Monsoon season. Winter crops, which are planted in November/December and harvested in June/July, are most probably affected by this prolonged dry spell throughout their growing season. On the other hand, for summer crops, the existing water allocation strategy based on a rotational basis has the potential to cause conflict among farmers.

4.2. Water balance modelling

The atmospheric demand on water from such crops in this region increases rapidly from the beginning of the year, reaching a maximum in April and May. Fig. 7, the reference evapotranspiration (ET_0) plot for Jomsom, Dhakarjong and Phalyak, shows this increase. With the arrival of the summer Monsoon in early June, evapotranspiration again starts increasing until October, thereafter exhibiting a steady decreasing trend in autumn (i.e. the post-Monsoon period).

ET_0 is estimated to increase by 20–45% in the study villages when extremes are considered. Fig. 7 shows this variation in reference evapotranspiration for average and extreme conditions; the variability is more pronounced during the winter Monsoon period. This significant variation in ET_0 between average and extreme climate conditions will tend to manifest in the crop water demand and will need to be considered for sustainable irrigation water management, especially in such arid mountainous regions. Based on the single crop-coefficient method, the potential evapotranspiration (ET_c) in mm for different crops is presented in Table 3.

While ET_0 represents the standard for evaporative demand of the environment and ET_c best describes the potential water use between the crops, it is the actual evapotranspiration (ET_a) that determines the timing and volume of irrigation to be applied to the crops. For farm-level irrigation, FAO 056 procedures (Allen et al., 1998) combined with a water-balance approach are usually employed for irrigation scheduling.

Irrigation is carried out on a rotational basis with total water shares of three days for 23 ha of fields in Phalyak, and two days for 9 ha of fields of Dhakarjong, respectively. In total, 32 ha are currently irrigated using water from the Lumbuk stream. As reported by

Table 3

Crop evapotranspiration in Dakarjong and Phalyak villages.

Major crops	Crop evapotranspiration, ET _c (m ³ ha ⁻¹) ^a				Total
	Crop development stage				
	L _i	L _{dev}	L _{mid}	L _{late}	
Naked wheat	179.29	952.25	2625.88	1101.93	4859.35
Wheat	179.29	952.25	2409.89	834.27	4375.69
Barley	134.46	457.51	1566.77	891.52	3050.26
Buckwheat (sweet)	260.27	727.96	1635.69	715.06	3338.99
Buckwheat (bitter)	260.27	606.64	1460.93	573.71	2901.55
Maize	327.32	916.35	1495.42	926.08	3665.17
Potato	327.32	916.35	1495.42	926.08	3665.17
Beans and pulses	369.89	723.18	1555.92	680.01	3329.01

^a Calculation based on plant date of June 15 for summer Crops and November 15 for winter crops; conversion factor of $1 \text{ mm} = 10 \text{ m}^3 \text{ha}^{-1}$ is used.

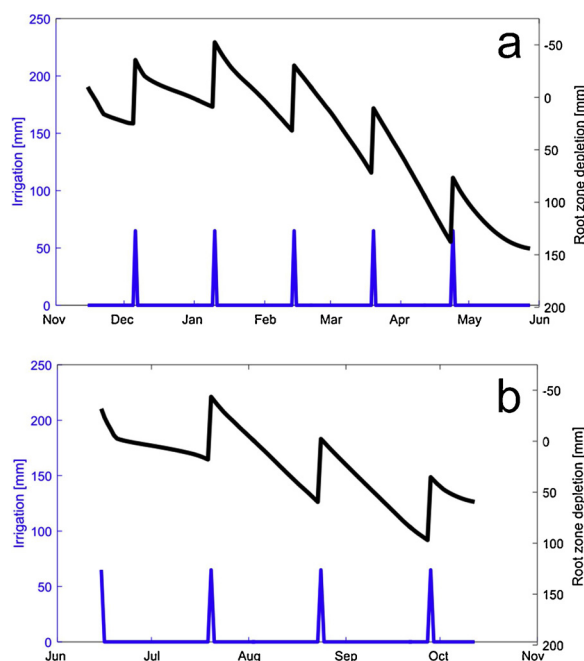


Fig. 8. WaSim soil moisture simulation showing root zone depletion for (a) winter crops; and (b) summer crops.

the farmers, the current irrigation system requires at least 30–35 days to irrigate all these fields. Considering the result from the hydrological analysis, a simple generalisation is performed for the approximate depth of irrigation currently applied to the fields. Flow that exceeds 95% of time ($Q_{95} = 0.0179 \text{ m}^3/\text{s}$) is taken for both winter and summer irrigation. A large portion of this diverted flow will be lost due to seepage, evaporation, and other factors occurring in the earthen water conveyance structures. So far, field application losses have also been high in basin/furrow irrigation. As there is no concrete information about the actual quantity of losses occurring in traditional furrow/basin irrigation, a reasonable irrigation efficiency of 40% has been assumed, which will allow an irrigation depth of ~65 mm for the irrigation interval of 30–35 days.

The daily soil moisture simulation for the current scenario is presented in Fig. 8. The current irrigation application is not in tandem with soil moisture demand: there is either too much water, resulting in deep percolation, or too little water, causing water stress in the crops. However, in both seasons, there is only a minor impact on the crop yield, as the simulation resulted in a relative transpiration of more than 95%.

4.3. Water management options and participatory monitoring

The aforementioned results contrast starkly against local perception, as local farmers find it hard to irrigate their fields and cannot grow crops as per potential yield. These differences can be explained by two plausible explanations. First, our initial assumption of 40% irrigation efficiency might not be accurate in this traditional farmer-managed irrigation system made up of earthen works. There could be substantial losses during the storage and conveyance through long earthen canals in the sandy loam mountainous terrain. Secondly, the very low daily streamflow and small pond sizes for seasonal storage irrigate very little land at once: farmers have to

Table 4

Optimum irrigation depth, gross irrigation requirement, and potential irrigable area.

Months for irrigation	Water requirement at field (WRF) (mm)	Water requirement for withdrawal ^a		Water available (m ³)	Potential irrigable area (ha)
		(mm)	(m ³ ha ^{−1})		
Winter crops					
Nov	10	25	250	86570	346.3
Feb	121	303	3025	52650	17.4
Mar	123	308	3075	58020	18.9
May	121	303	3025	50990	16.9
Summer crops					
Jun	13	33	325	44540	137.0
Aug	112	280	2800	177710	63.5
Sep	113	283	2825	106410	37.7

^a Overall irrigation efficiency is assumed to be 0.4.

wait more than a month for their turn. This delay could possibly lower the crops to the irrecoverable water stress point.

Table 4 provides the optimum irrigation schedule for the current mixed cropping pattern. Since streamflow in summer is sufficiently high, the irrigation schedule can be optimised during this cropping period; the irrigable area could be substantially increased. With the current diversion already inadequate to support crops in the pre-Monsoon period, additional depth during this period cannot be supported unless there are other sources to complement the deficit. Unlike pumping irrigation systems, where the number of operations is more important than the flow, in gravity systems like this, the water availability in the river becomes the only limiting factor determining the optimisation schedule. Hence, other management options need to be explored, particularly for winter irrigation management.

The overall water balance shows that irrigation, particularly at the start of the cropping season, can be reduced substantially: the potential evapotranspiration for crops during the vegetative growth is lower; also, climatic conditions are not extreme during these months. Therefore, a late start to irrigation during the crop growth stage is highly recommended. However, the high variability of flow during summer has to be taken into account for the optimisation of the irrigation schedule during this period. One major limitation to our assessment here is the length of our dataset. A one-year window is probably insufficient to capture long-term variability in precipitation time series, which is likely in the face of climate change. However, in spite of data brevity and of the need for longer time series, we are able to recommend some water management options.

Both the existing irrigation pattern and the optimum scenario assume the overall efficiency of irrigation to be at least 40%; ideally, for basin/furrow irrigation, this assumption is reasonable (Brouwer et al., 1989). Yet in this instance, a very small fraction of flow is available to crops due to significant losses in transition. As a local response towards these potential losses, locally modified fields into levelled terraces can be seen in the region; but they only serve to regulate the water volume reaching the farm field. Improvements in terms of making concrete water reservoirs, lined canals or conveyance through pipes have already been seen in other villages of the Upper Mustang region (Basnet, 2007).

However, such improvements are generally costly, time-consuming, and may not produce immediate or tangible benefits at the local level. Recently, citizen science has emerged as a more useful tool in WRM to energise local stakeholders, placing them at the heart of decisions regarding water resources (Paul et al., 2018; Paul and Buytaert, 2018). Non-scientist-collected data can enhance and densify more traditional datasets in space and time; while rapid technological advances in the last 10–15 years and the ubiquity of low-cost ‘smart’ sensors in everyday devices like smartphones (part of the Internet of Things: Gubbi et al., 2013) have increased the feasibility of participatory data collection within a devolved monitoring framework (Buytaert et al., 2014; Paul et al., 2018).

This approach has been demonstrably successful in complementing existing government-operated hydrometric networks in data-scarce regions like western Nepal and elsewhere (Buytaert et al., 2014). A useful means of densifying existing sensor networks in space and time, thus improving monitoring robustness, could be the installation of low-cost river level sensors and rain gauges. Paul et al. (2018) describe this process, where non-scientist local stakeholders can be trained to read and download data, which can then ideally be transformed into actionable information like river flow forecasts, which are transmitted back to community members via, for instance, smartphone apps, SMS alerts, or knowledge dissemination interfaces (e.g. Buytaert et al., 2014; Zulkafli et al., 2017; Paul et al., 2018). In addition, in the UKGRB, additional deployment of low-cost, non-scientist-maintained soil moisture sensors (e.g. that use time-domain reflectometry), and lysimeters to measure evapotranspiration, could be carried out, where the sensors are connected to a high-precision clock that times irrigation patterns in a “smart” manner (e.g. precluding irrigation following recent rainfall episodes: Bogenia et al., 2010).

Moreover, these citizen-sourced data also complement and can be combined with remotely-sensed data (e.g. precipitation: Manzan et al., 2016). Extensive ground-based observations are increasingly needed for calibration and to resolve small-scale spatiotemporal processes, which is especially important in complex mountainous regions such as the UKGRB.

Although participatory projects have been common in WRM for some time, the uptake of citizen science has been rather limited in hydrological research in southeast Asia (Buytaert et al., 2014). One possible reason could be the difficulty in interpreting complex hydrological data intuitively, with intensive scientific training normally being a pre-requisite for subsequent data analysis. However, as we have argued above, new technology has the possibility to circumvent these limitations. Participatory projects also have the potential to bring tangible benefits to isolated communities like Dakarjong and Phalyak, such as increased scientific literacy and political empowerment and engagement. Indeed, such projects have been shown to work best when there is active local buy-in, and the benefits to local stakeholders are highlighted (Paul et al., 2018). Participatory engagement, however, must be handled sensitively: new scientific insights could potentially cause apprehension, while improper communication of results could risk the creation of permanent misunderstandings (e.g. Seymour and Regalado, 2014). It is therefore important to understand the livelihood needs, capacity, and specific vulnerabilities of local stakeholders prior to any scientific work. Communication pathways between scientists, citizen scientists, and non-participating community members should be mapped, along with existing social hierarchies and power relationships. In this way, the most appropriate point of entry for an intervention can be sought; while regular mentoring and information feedback/training sessions have been shown to build trust between scientists and citizens, promoting long-term project sustainability (e.g. Buytaert et al., 2014; Rotman et al., 2014).

5. Conclusions and future outlook

Although the Himalayas are a major reservoir of freshwater, the remote mountain communities that host highly poor and marginalised groups have difficulty exploiting the full potential to support their subsistence farming and agro-pastoral livelihoods. The complex physiography, changing environmental dynamics and the effects of climate change have all added huge uncertainty to water availability in the region. Often these effects are more severe in the rain-shadow region, such as in the Upper Kaligandaki River

Basin (UKGRB), where the Monsoon is less important and water is primarily provided by glacial meltwater. A lack of hydro-meteorological data has further impeded understanding of the mountain hydrology to formulate sustainable WRM strategies in these fragile regions. To date, there have been hardly any national-level policy interventions here; in this context, an attempt was made to employ a location-specific intervention tailored to the citizen science concept to generate hydrological knowledge for improving WRM in the UKGRB.

Mountain streams demonstrate a large variability in summer flow, whereas flow is reduced dramatically and almost remains stable for the other seasons, which contrasts with the usual bimodal peaks of rivers in the Trans-Himalayan region. Due to the lack of knowledge about local water availability and crop water demand, deficit irrigation has been practised extensively in the study area. The existing cropping pattern focuses on crops that have high water demand in prolonged dry spells, which would have a severe impact on crop yield. Apart from the natural limitations of water, the lack of efficient irrigation infrastructures further limits access to water. Some flexibility in cropping dates and patterns could reduce crop water requirements and allow for a more equitable distribution of available seasonal flow. However, considering the increased variability in streamflow, these procedures cannot be recommended as a sustainable solution for the future. In the long term, either a major shift from (non-subsistence) cereal crops to tree crops is recommended; while the construction of a reservoir for seasonal storage could ameliorate the local seasonal deficit of water.

Our research methodology has been applied only to two specific communities; yet it has the potential to be scaled up to the entire UKGRB. Water availability, improved irrigation systems, and the need for technical assistance for improved WRM, have all been reported as common priorities for local farmers in the Mustang district. We have suggested that a citizen science approach for participatory monitoring and the co-generation of hydrological knowledge could lead to potential entry points to make such scaling up a reality, as well as greatly densifying existing hydrological monitoring networks in space and time. This bottom-up approach could complement, and improve upon, the more traditional top-down approach that has met with lower degrees of success in addressing water security issues in remote mountainous villages of Nepal.

Conflict of interest statement

We declare no conflict of interest.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:<https://doi.org/10.1016/j.ejrh.2019.100604>.

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