Hydrology Research

Hydrology Research Vol 53 No 11, 1340 doi: 10.2166/nh.2022.027

Identification of suitable sites for traditional *pokhari* water harvesting in mountain rural communities of the Himalaya

Eleonora Forzini [a,*], Luigi Piemontese [a], Elena Bresci [a], Blandine Barthod[b], Florian Bielser[b], Marc Sylvestre[b], Nirmal Adhikari[c], Sony Pun[c] and Giulio Castelli [a]

[a] Department of Agriculture, Food, Environment and Forestry (DAGRI), University of Florence, Via San Bonaventura, 13, Firenze 50145, Italy
[b] International Rainwater Harvesting Alliance (IRHA), Chemin de Balexert 9, 1219, Châtelaine, Geneva, Switzerland
[c] Kanchan Nepal (KN), Janapriya Marg-7, Pokhara, Nepal
*Corresponding author. E-mail: eleonora.forzini@unifi.it

EF, 0000-0001-6727-3706; LP, 0000-0002-1600-5450; EB, 0000-0002-1988-1720; GC, 0000-0002-1600-5450

ABSTRACT

Storing runoff during the monsoon season in Himalayan hills is crucial to have enough water to cope with the dry season, especially considering that climate change is changing rainfall intensity and patterns. Traditional Nepalese water ponds, called *pokharis*, are used to store runoff mainly for cattle rearing and rice fields' supplementary irrigation. Local communities are interested in restoring existing *pokharis* and building new ones to improve their economical and living conditions. Selecting the most suitable locations for *pokharis* is of crucial importance; however, scarce information is available for large-scale site selection. A comprehensive analysis of multiple relevant parameters for traditional ponds siting can lead to more efficient rainwater collection and provide a useful water resource management tool. In this work, we propose a methodology for *pokharis*' best-siting analysis, based on geographic information system (GIS), multi-criteria decision-making (MCDM), and participatory research. To our knowledge, this is the first large-scale best-siting analysis for traditional ponds in Nepal. An area of 0.423 km^2 (3.47% of the study area) is classified as highly suitable, with 100% agreement with existing *pokharis*. Despite the low data resolution, which requires a further field inspection for the final site selection, our results provide reliable guidance for *pokharis*' large-scale suitability, supporting water-resilience projects in the area.

Key words: drought, spatial multi-criteria analysis, sustainable water management, water harvesting best siting, water harvesting ponds

HIGHLIGHTS

- Large-scale best-siting analyses of traditional Nepalese ponds (*pokharis*) are lacking despite their importance for water management in Nepal.
- Uphill communities, being more prone to water scarcity, were prioritized through appropriate criteria setting.
- We propose a composite of standard and in-field surveyed criteria for *pokharis*' best siting.
- The study provides useful guidance for building water harvesting ponds in Nepal.

INTRODUCTION

For centuries, farmers have adapted to climate variability by implementing various kinds of practices including soil and water conservation techniques and water harvesting (WH) (Al-Adamat *et al.* 2012; Adhikari 2018). This latter includes a wide range of techniques aimed at storing runoff water in the soil or dedicated structures to use it subsequently for productive purposes (Adhikari *et al.* 2018; Subedi *et al.* 2020). WH has been applied in many areas of the world through low-cost and eco-friendly interventions, developed from the indigenous knowledge of local people (Lal & Verma 2008; Chen *et al.* 2019). In mountainous areas, where water availability is a major concern, WH allows extending the cropping season and increasing food security by providing water while conventional water sources are drying out (Subedi *et al.* 2020). Moreover, it reduces soil erosion and flood risk and can increase water infiltration in soil and groundwater downstream (Lal & Verma 2008; Dile *et al.* 2016). WH has been proven to considerably increase crop yields, soil moisture, and farmers' income; and to reduce soil erosion in various mountainous zones of the world, among which the Himalayan region, including Nepal (Bastakoti *et al.* 2016; Adhikari 2018; Adhikari *et al.* 2018; Subedi *et al.* 2020).

Nepal is a landlocked country in the Himalayan region (UNDP 2020). Moving from North to South, the Nepalese climate ranges from an extremely cold subarctic climate to a monsoon-influenced tropical one, covering the Köppen and Geiger classification codes Dfd, Dwc, Dwa, Cwb, and Cwa. Despite being perceived as a water-rich country, with a mean annual rainfall of 1,344 mm, some areas of Nepal suffer from water stress during the dry season, especially from March to June (Adhikari 2018). The reason is the unbalanced rainfall distribution throughout the year with about 80% of total annual precipitation limited to the monsoon season between June and September (Adhikari *et al.* 2018). Moreover, climate change is altering rainfall patterns and decreasing total precipitation (Adhikari 2018; Subedi *et al.* 2020). Climate change consequences can be particularly severe in Nepal, where around 80% of the population depends on subsistence agriculture, especially in hilly areas, and more than 50% of agricultural land is rainfed (Subedi *et al.* 2020). Nepalese farmers report an increased frequency of droughts, late monsoon onset, rising temperatures, reduction of water availability, and flooding during monsoon as major impacts on their livelihoods (Bastakoti *et al.* 2016). If monsoon onset is delayed, farmers need to irrigate their crops to avoid severe crop losses (Bastakoti *et al.* 2016; Pandey 2019).

Traditional Nepalese ponds called *pokharis* (Bastakoti *et al.* 2016) are used, especially in rural areas, to harvest and store rainwater for supplemental irrigation, cattle rearing, fish farming, fire control, recreational, and sometimes domestic uses (Lal & Verma 2008; Chen *et al.* 2017; Subedi *et al.* 2020). Very similar structures can be found also in India and China (Lal & Verma 2008; Chen *et al.* 2017, 2019). They are hand-dug, shallow (1.2–1.5 m) generally small ponds (extended from a few to 500 m^2), but their dimension can vary substantially (Lal & Verma 2008; Bastakoti *et al.* 2016; Chen *et al.* 2017, 2019). The bottom of the *pokharis* is lined with red loamy soil compacted by animal passage, while lateral walls are covered with stones and red soil to be impermeable. Each pond also presents two stairs to allow animals access to the pond itself. Maintenance is carried out by village communities. *Pokharis* (Figure 1) are built near housing and fields, but they can be found also near roads and forests when cattle rearing is their main use (Lal & Verma 2008). They also have an important socio-cultural value, as people usually meet near ponds to rest during daily activities and socialize (Chen *et al.* 2019).

Recently, *pokharis* are being abandoned due to the development of irrigation facilities in some areas, while many others are degrading because of abandonment of farmlands (Chen *et al.* 2017, 2019). Underutilization and poor management of these traditional structures reduces not only water availability in dry months but also ecosystem services provided by *pokharis* like downhill flood risk reduction and sediment control (Lal & Verma 2008; Bastakoti *et al.* 2016; Chen *et al.* 2019).

Various authors (Lal & Verma 2008; Bastakoti *et al.* 2016; Chen *et al.* 2017; Adhikari 2018), also reporting farmers' opinions, point out that restoring existing *pokharis* and building new ones could foster resilience to climate change through

Figure 1 | Picture of a *pokhari*, taken during a field visit in October 2021 in the study area.

increased water availability. Usually, the construction sites of new *pokharis*, and ponds in general, are selected 'arbitrarily', considering only the proximity to the point where water is needed (Chen *et al.* 2017).

However, a more comprehensive and systematic site selection can lead to more efficient WH structures, which in turn contribute to improving water availability and agricultural productivity (Adham *et al.* 2016; Mugo & Odera 2019). Nevertheless, site selection is a very challenging task especially at large spatial scales, owing to the lack of detailed hydrological and soil data (Singhai *et al.* 2019).

In the last three decades, many studies have attempted to identify the most suitable sites for different types of WH structures, often using geographical information system (GIS) and multi-criteria decision-making (MCDM) (Adham *et al.* 2016). GIS is widely used because it allows us to analyze large areas by integrating spatial physical and socio-economic information in a timely and cost-effective way (Adham *et al.* 2016). On the other hand, MCDM allows us to compare and relate different kinds of data producing a single final output displaying various options (Krois & Schulte 2014).

The literature on the topic reports the need to select some criteria for WH structures' best siting, such as environmental and physical characteristics of the area of interest, and its socio-economic features (Adham *et al.* 2016; Grum *et al.* 2016). Common physical criteria considered for best-siting analysis are slope, soil type, runoff, and land use (Al-Adamat *et al.* 2012; Dile *et al.* 2016). On the other hand, the main socio-economic data are the distance from roads, villages, and fields (de Winnaar *et al.* 2007). In several cases, these latter criteria and participatory activities to assess stakeholders' preferences are neglected despite being necessary to ensure the proper implementation of site-specific effective measures (Adham *et al.* 2016; Grum *et al.* 2016).

In this work, we use MCDM and GIS to produce, to our knowledge, the first best-siting analysis for *pokharis*. While considering similar MCDM parameters as other conventional best-siting studies for WH structures, we include innovative parameters, such as upslope contributing area and elevation.

Finally, we complement the geophysical analysis with community-driven criteria, including indigenous knowledge, to integrate and validate our analysis.

STUDY AREA

The study area is in the north-eastern Kaski district, Nepal. This district lies in the mid-hill ecological region of Nepal, in the central-western part of the country (Figure 2). It is located in the monsoon-influenced tropical climatic zone and the mean annual rainfall in this region, which is the highest in Nepal, is around 3,900 mm, the majority of which (60–90%) occurs during the monsoon season from June to September (Subedi *et al.* 2020). The average annual temperature nearby Pokhara city, at 854 m a.s.l., is 18.3 °C. From a socio-economical point of view, the Kaski district is characterized by high rates of out-migration, both towards other districts or countries and within the district itself, from less productive upland areas towards downhill zones and Pokhara city. This leads to farmland degradation and abandonment, especially in more marginal and poor areas of the Kaski hills (Pandey 2019).

The study area, which is around 1,186 km^2 large, ranges between 28°12′51″N, 84°4′26″E and 28°10′37″N, 84°11′53″E. The elevation ranges from 407 m to 1,443 m a.s.l. South-facing slopes are usually terraced for cultivation, while North-facing slopes of forest and shrublands do not receive enough solar radiation to allow for cropping.

Our analysis focuses on four communities within the study area: Thulakot, Majhkot, Begnas, and Hansapur (hereon 'locations of interest'), considered representative of the local socio-economical setting. The four locations of interest are also characterized by their position on the upslope parts of the watersheds in the hilly mountainous area, located in the northern surroundings of Pokhara city (Figure 2). These locations (i.e. upslope and south-facing) have been selected since they are the most prone to water scarcity. The total area of the location of interest is 12.11 km^2.

DATA

All the datasets used in this work – i.e. soil type, European Space Agency (ESA) Worldcover Land Use/Land Cover (LULC) map and a Digital Elevation Model (DEM) – were downloaded from websites of different public agencies. Flow accumulation (also said upslope contributing area), slope, and elevation maps were derived from the DEM through QGIS software. The lakes and rivers spatial data retrieved by Open Street Map were provided by the International Rainwater Harvesting Alliance (IRHA), a Swiss NGO carrying out a project in this area with its Nepalese local partner NGO Kanchan Nepal. We downloaded a gridded soil map from the Nepalese National Soil Science Research Center (NARC) website. The soil data were

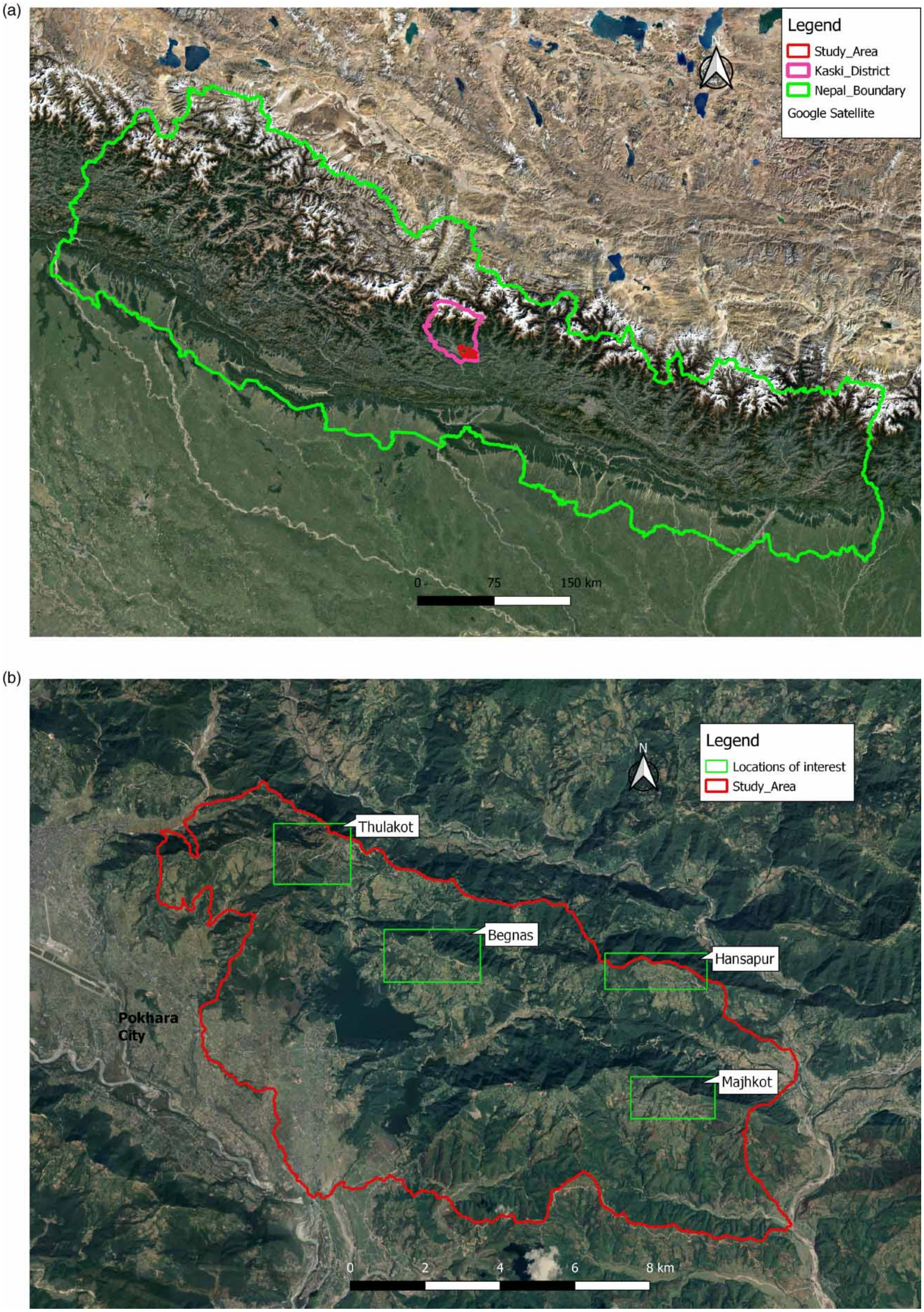

Figure 2 | (a) Study area (red line) within Nepal (green line) and Kaski district (pink line); (b) zoom on the four top hills object of this work within the study area. Please refer to the online version of this paper to see this figure in colour: https://dx.doi.org/10.2166/nh.2022.027.

developed with machine learning and predict soil conditions up to 2 m. Kanchan Nepal provided some GPS locations of existing *pokharis* in the study area as well, while some other locations were gathered during a field visit in the same zone. Data on terraced and private areas, and traditional criteria considered in *pokhari* building, were collected during the field visit. This work was carried out in the framework of IRHA's project. Table 1 reports the sources from which we accessed the data.

METHODS

Methodological framework: multi-criteria decision-making

Spatial MCDM procedures, also known as the weighted overlay process (WOP), are used to combine different thematic maps through a few simple steps to obtain a single final suitability map (Krois & Schulte 2014; Adham *et al.* 2016). A suitability map allows us to visualize multiple options ranked based on preferences expressed through the categorization of various criteria, weighted depending on the influence they have on the overall objective (Al-Adamat *et al.* 2012). The methodological steps of MCDM can be summarized as follows (Grum *et al.* 2016):

1. Selection of relevant suitability criteria for achieving the objective;
2. Establishment of suitability ranges for each criterion (usually on a scale from 1 to 9 where 9 represents the optimal value) and normalization of each criterion on a 1–9 scale;
3. Assignment of a weight to each criterion according to the influence they have on the result – potentially according to experts or local people's opinions. Regardless of their distribution, the sum of all weights must be 1.
4. Combination of suitability values of all weighted criteria to produce the final suitability map.

For each cell of the suitability map, the final suitability score (S) is calculated as follows:

$$S = \sum_i w_i \cdot x_i \quad (1)$$

where w_i is the weight of factor i and x_i is the suitability score of factor i (Dile *et al.* 2016).

In the present study, the MCDM process was structured in two stages, as shown in the flowchart of the methodology (Figure 3). As a first step, we reviewed various best-siting papers for WH structures applying MCDM and GIS to select the relevant criteria for our work (Literature review). Based on the review, a preliminary set of bio-geophysical criteria and relative weights was defined, which was later used to generate a first preliminary version of the best-siting map. The robustness of the preliminary map was cross-checked with two tests: (a) a sensitivity analysis performed by changing the weights of the MCDM equation, following the approach of Dile *et al.* (2016); and (b) a validation of the most suitable areas, carried out by analysing the value S of the GPS locations of existent *pokharis*. The second step of the analysis allowed a refinement of the suitability map, by maximizing the findings on the on-site survey, aimed at gathering additional information such as terraced and private areas and identifying new socio-economic criteria through a participatory analysis. A new set of

Table 1 | Main information on data sources and format

Data	Data format	Source
Soil	Raster (250 m resolution)	Nepalese National Soil Science Research Center (NARC) website (accessed 21 May 2021)
LULC	Raster (10 m resolution)	ESA Worldcover 10 m 2020 Product (Zanaga *et al.* 2021) (accessed 5 October 2021)
Digital Elevation Model (DEM)	Raster (30 m resolution)	Japan Aerospace Exploration Agency (JAXA), 2021 data (accessed 10 May 2021)
Water sources	Vector	International Rainwater Harvesting Alliance (IRHA) (NGO)
Existing ponds GPS position	Vector	Provided by Kanchan Nepal and Collected during Field visit (21–25 October 2021)
Terraced and private areas	Vector	Collected during Field visit (21–22 and 24–25 October 2021)
Pokhari building traditional criteria	Text	Collected during Field visit (20–22 October 2021)

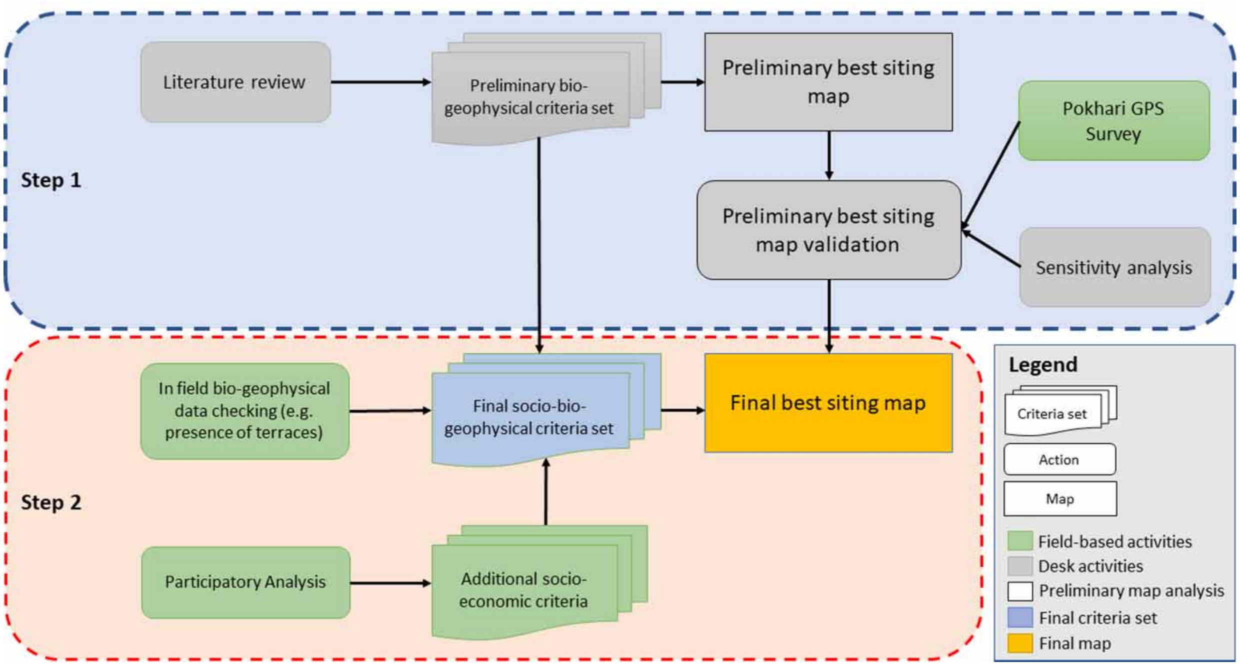

Figure 3 | Flowchart of applied methodology.

socio-bio-geophysical criteria was then obtained merging the criteria of step 1 and of step 2. The additional socio-economic criteria were included by selecting all the areas in the preliminary map falling in the highest quartile of *S* score (Q4) and removing the ones not meeting the criteria, in order to display only highly suitable areas fitting with socio-economic features. In fact, in our case, these latter do not allow for a suitability range but are rather Boolean criteria, which can only match or not match a given condition.

Literature review and preliminary bio-geophysical criteria set

We reviewed various best-siting works carried out using MCDM and GIS focusing on ponds in different geographic areas and selected the most relevant criteria for the objective of the analysis (de Winnaar *et al.* 2007; Al-Adamat *et al.* 2012; Dile *et al.* 2016; Grum *et al.* 2016). As summarized in the review paper of Adham *et al.* (2016), the most common criteria are slope, soil type, and land use. Other common geophysical criteria are rainfall and runoff, while the main socio-economic criteria are the distance from roads, villages, streams, and fields. The slope affects the quantity of rainfall that infiltrates into the soil or runs off, the distribution of runoff, and the quantity of earthwork needed to build WH reservoirs (Ramakrishnan *et al.* 2009; Dile *et al.* 2016). Moreover, a small slope is needed to convey water towards storage sites, thus gentle slopes are preferred for WH implementation with respect to flat areas (Ward *et al.* 2021). The soil type affects water infiltration and storage in the soil (Mugo & Odera 2019), and consequently, the runoff (Singhai *et al.* 2019). Soil type suitability varies with the type of WH structure. For instance, sandy soils are better suited for recharge structures, while clayey soils are preferred for water storage structures, such as ponds (Al-Adamat *et al.* 2010; Adham *et al.* 2016). LULC informs on land surface characteristics (Ward *et al.* 2021). These latter control the quantity of runoff produced in an area, and water infiltration in soil (de Winnaar *et al.* 2007). It can be easily extracted by remote sensing data (Adham *et al.* 2016). Rainfall quantity is usually considered in WH best siting to locate areas where more runoff is generated, as it can be used to recharge the structures (Chen *et al.* 2017).

Concerning socio-economic criteria, distance from houses and cropped fields are considered because harvested water is mainly required for domestic and agricultural use, thus structures should be as close as possible to where water is needed (de Winnaar *et al.* 2007; Chen *et al.* 2017). The same occurs for roads, from which WH structures can be easily accessed. Distance from streams is sometimes considered since part of streams' discharge can be used to recharge WH structures (Al-Adamat *et al.* 2010).

Following the literature analysis, the selected parameters considered in this analysis are slope, LULC, soil type, upslope contributing area, elevation, and distance from rivers and lakes. In our case, we decided to introduce an upslope contributing area as a proxy for the presence of minimum water flow (which can feed *pokharis*) instead of estimating runoff. The upslope contributing area represents the area draining water to a downstream point, and it is measured in km^2. It is higher in riverbeds and lower in upslope zones (Chen *et al.* 2017). We did not include a rainfall layer because, due to monsoons, our study area receives enough rainwater, thus prioritizing areas with higher rainfall is unnecessary. Distance from fields and settlements was considered at a later stage of the final analysis, to include the outcomes of the field visit, as these criteria were indicated directly by local people.

Elevation and distance from rivers and lakes were both used to prioritize areas more prone to water scarcity, which are those more uphill and further away from rivers and lakes (which contribute to groundwater recharge and irrigation).

Preliminary best-siting map

The value ranges/categories of each layer were given a suitability score spanning from 1 (unsuitable values/categories) to 9 (optimal values/categories – suitability scores are referred to as x_1 in Equation (1)). Regarding the suitability score given to each value range of each criterion, we assigned them as follows: According to the literature, optimal values for slope for ponds best siting range from 0–3% to 0–5% (Ramakrishnan *et al.* 2009; Al-Adamat *et al.* 2010). On this basis, we assigned the highest suitability score to the 0–3.5% slope range. To other ranges of increasing slopes are assigned decreasing suitability values as summarized in Table 2. Regarding the upslope contributing area, we assigned the highest suitability score (9) to contributing areas of 0.09–0.18 km^2, considering that the quantity of runoff should be enough to recharge *pokharis* but not too high to prevent structural damages. This range was selected by adapting to our study area the upslope contributing area values proposed by Márquez *et al.* (2021). Consequently, upslope contributing areas higher than 0.18 km^2 were given lower suitability, while contributing areas smaller than 0.09 km^2 were given an intermediate suitability score. In the case of farm ponds, usually, the highest suitability score for land use is given to agricultural land if water is used for irrigation (Dile *et al.* 2016), while when ponds are used mainly for herding, also shrubland, bareland, and grassland areas can be marked as optimally suitable (Grum *et al.* 2016; Singhai *et al.* 2019). Another reason for which we did not assign the highest suitability score to cultivated land is that in our study area, cropped fields are terraced, thus it is not advisable to build ponds there in order to cultivate all the available surface. Moreover, in our locations of interest shrublands, barelands and grasslands are usually located near cultivations, thus the collected water can be easily accessed for supplementary irrigation as well. Furthermore, the land use map used in this work marked as 'forest' all the areas with a tree cover $>10\%$, thus, not having information on the actual presence of open forest (which could have been very suitable for ponds) and closed forest (not suitable as there would not be enough space for a pond), we decided to assign it an intermediate suitability score. According to the literature (Al-Adamat *et al.* 2012; Adham *et al.* 2016; Ward *et al.* 2021), less-draining soils such as clay, silty loam, and loamy soils are ideal for ponds construction. We gave both silt and silty loam soil a suitability value of 9. The highest elevation and distances from water bodies were assigned maximum suitability in order to prioritize more water-scarce areas which cannot benefit from this surface water and groundwater recharge. Hence, zones closer to water bodies were given lower suitability. Table 2 summarizes suitability values assigned to each criterion category and sources used to set the suitability ranges.

Following the MCDM steps, each layer was given a weight based on the relative influence on the resulting map. Weight assignment is a complicated task that might produce misleading results (Al-Adamat *et al.* 2012). Weights of criteria for MCDM are computed mainly through the Analytical Hierarchy Process (AHP) method which allows us to assign weights by comparing the selected criteria in a pairwise matrix and inspecting the relative importance of each layer (Grum *et al.* 2016; Ward *et al.* 2021). The pairs of criteria are set according to literature and experts' opinions (Krois & Schulte 2014; Ward *et al.* 2021) or through participatory workshops with stakeholders and NGO consultants (Grum *et al.* 2016). However, AHP is highly influenced by expertise (Adham *et al.* 2016). Sometimes, weights are assigned directly on the basis of literature or opinions, without applying the pairwise matrix (Al-Adamat *et al.* 2010; Krois & Schulte 2014) or equal weights are assigned to all the criteria to avoid biases (de Winnaar *et al.* 2007; Al-Adamat *et al.* 2012). Owing to these reasons, we decided to assign equal weights to all the layers except for the distance from water bodies, which received a lower weight. Distance from rivers and lakes serves to prioritize areas that cannot likely count on groundwater recharge or surface water for agriculture. However, stream water cannot always be easily accessed in hilly areas, so this criterion has a lower influence on the final selection of best sites. We considered this weight setting since it is the most conservative and balanced.

Table 2 | Suitability scores and sources used for setting the suitability ranges used in the analysis

Suitability score	9	7	5	3	1	Range source
Slope (%)	0–3.5	3.6–7	7.1–10	10.1–15	>15.1	Literature
Upslope contributing area (km^2)	0.09–0.18	0.1809–0.269	0.27–0.359 and <0.09	0.36–0.489	>0.49	Literature and GIS analysis
LULC type and class ID number	– grassland (30) – shrubland (20) – bareland (60)	– Forest (10)	– Cropland (40)	–	– Permanent water bodies (80) – Urban/built-up land (50)	Literature
Soil type	Silty, silty loam	–	–	–	–	Literature
Elevation (m a.s.l.)	1,237–1,445	1,029–1,236	821–1,028	613–820	1–612	GIS analysis
Distance from lakes and rivers (km)	>4	3–3.9	2–2.9	1–1.9	<0.99	GIS analysis
Terraced and private areas[a]	–	–	–	–	–	GIS analysis

[a]These features have been removed using a Boolean operator which either includes or excludes a map area in the analysis according to specific criteria, thus no weight setting is required in this case. We set the operator to exclude terraced and private areas recorded on the field from the suitability map obtained through the GIS.

Sensitivity analysis

We performed a sensitivity analysis to assess the variability of the results at varying weights of the best-siting criteria, as a measure of uncertainty following Dile *et al.* (2016). We first assigned equal weights to all the criteria (variation 1). We then varied the weights of each criterion using plausible strategies. In variation 2, the highest weight was given to slope, which is usually assigned a higher weight (Al-Adamat *et al.* 2010; Singhai *et al.* 2019). Usually, the soil is weighted slightly higher than land use (Mbilinyi *et al.* 2007; Krois & Schulte 2014), thus we also tested soil type influence on the result in variation 3. The fourth variation was set to give land use the highest weight, while in variation 5, we tested the influence of upslope contributing area on the result by attributing the highest weight. Table 3 summarizes the tested weight distributions.

In field bio-geophysical data checking and participatory analysis

We conducted a field visit in the study area between the 16th and the 30th of October 2021 with three specific objectives: (a) surveying additional GPS locations of existing traditional ponds beyond the 13 ones provided by Kanchan Nepal to validate the preliminary best-siting results (*pokhari* GPS survey); (b) collecting information on land ownership and terraces presence; (c) gathering information on traditional criteria for selecting suitable *pokharis*' locations.

Concerning the validation of the preliminary results, we checked in which suitability quartile the existing *pokharis* are located. Those found within the high suitability areas obtained with the preliminary GIS siting were considered successful. Field inspection of suitable areas was also carried out to check for 'false positives', i.e. areas with theoretical high suitability, but with local constraints hindering the construction of *pokharis* (e.g. presence of agricultural terraces or private land ownership).

The features resulting as 'false positives' were then removed from high suitability areas in the final map. Finally, we complemented our set of siting criteria with the indigenous knowledge (additional socio-economic criteria) to account for potentially locally relevant factors that are usually neglected in best-siting studies. Traditional criteria to locate new ponds were surveyed through two focus group discussions with two different groups of local *pokharis* building experts (i.e. four people in Hansapur and seven people in Majhkot communities). They were all elder men who accompanied the authors to visit existing *pokharis* nearby their villages together with Kanchan Nepal members. These latter had already gained local people's trust during years of collaboration in development projects carried out in the same villages. During traditional ponds inspections, the NGO members also facilitated our interviews by translating from Nepalese language to English. Villagers were asked the following simple questions.

- How do you select where to build new *pokharis*? What factors do you consider?
- Which are the features characterizing these ponds?

We then complemented our criteria set with the interviewees' socio-economic criteria to obtain the final best-siting map, including the information obtained on the field. The integration of the traditional criteria into the GIS work was done by visual inspection, owing to the lack of digital layers. We selected and displayed from the preliminary map shown in Figure 4 all the areas falling on the highest suitability quartile (Q4) and removed from them the features pointed out by local people using a Boolean operator in Qgis software.

Table 3 | Different weight variations tested in the sensitivity analysis

Criterion	Weights	Variation 1	Variation 2	Variation 3	Variation 4	Variation 5
Slope	0.19	0.16	0.35	0.15	0.15	0.15
Soil type	0.19	0.16	0.15	0.35	0.15	0.15
LULC	0.19	0.16	0.15	0.15	0.35	0.15
UCA	0.19	0.16	0.15	0.15	0.15	0.35
Elevation	0.19	0.16	0.15	0.15	0.15	0.15
Distance from water bodies	0.05	0.16	0.05	0.05	0.05	0.05

UCA, upslope contributing area.

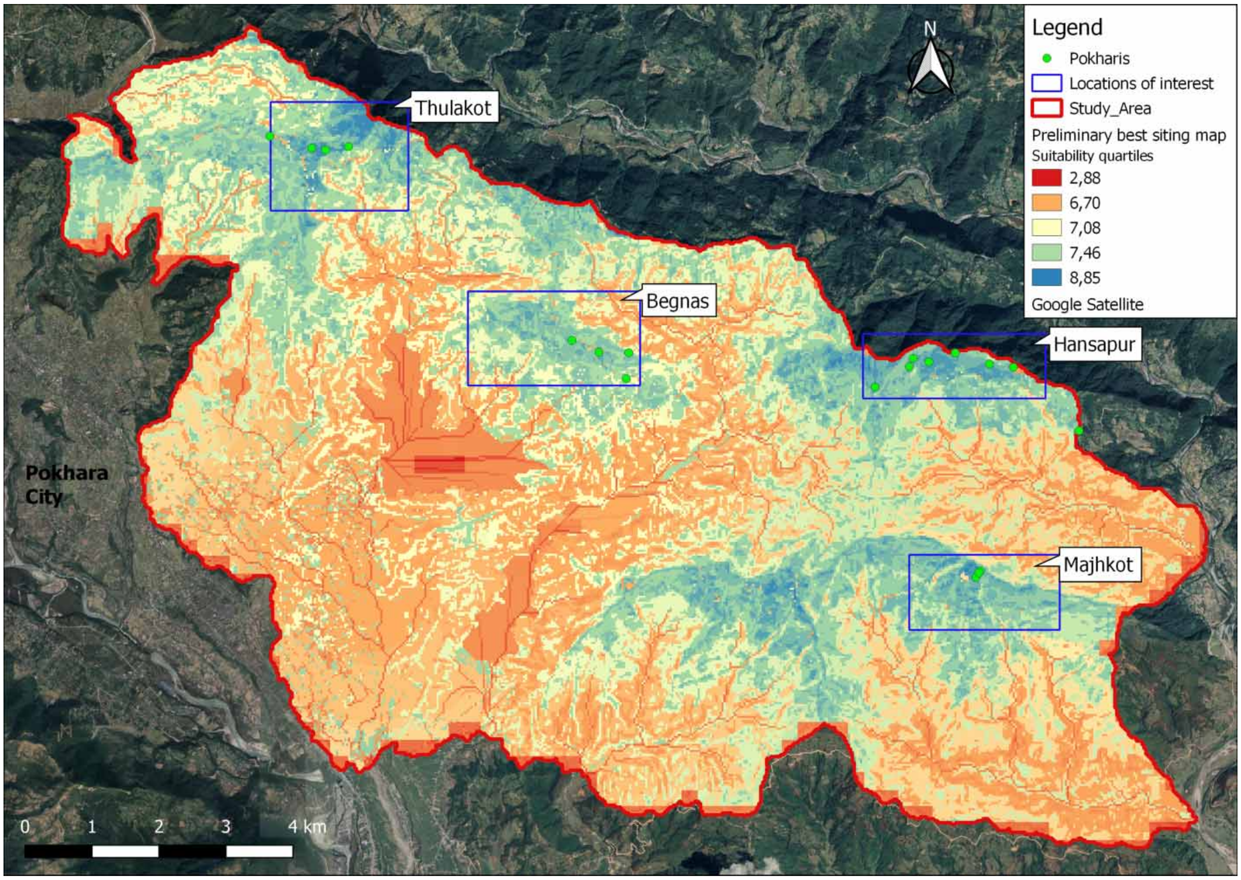

Figure 4 | Preliminary best-siting map.

RESULTS

Preliminary best-siting map

The preliminary best-siting map is shown in Figure 4. Unsurprisingly, higher suitability values lie in areas of higher elevation – where people rely on *pokharis* the most – which were given the highest priority. On the other hand, the lowest suitability values are reported in pixels corresponding to permanent water bodies followed by urban areas (Figure 4).

Sensitivity analysis

The results of the sensitivity analysis show only slight differences in the percentages of areas covered by high suitability zones (quartile 4) and unsuitable areas (quartile 1) in the six suitability maps obtained with the different weight conditions. A slightly higher variability is found in the two intermediate suitability quartiles, as shown in Figure 5. As expected, the influence of soil type on the result was negligible even in variation 3 given the homogeneity of soil types in our study area. Among the weight variations, the layer with the lowest percentage of high suitability area is variation 4, which assigned the highest relative importance to the LULC map. This is in contrast with Dile *et al.* (2016), who found rainfall to be the most restrictive criterion. Also in other works, land use is one of the most common criteria (Adham *et al.* 2016) but it is usually given a quite low weight (Mbilinyi *et al.* 2007; Singhai *et al.* 2019) while its influence on the result in our case was considerable. Furthermore, the spatial distribution of the suitability quartile is quite homogeneous among the different maps as well, as shown in Figure 6.

Preliminary best-siting map validation

After the sensitivity analysis, the Suitability score of pixels corresponding to the 20 existing *pokharis* GPS position was inspected. Figure 7 shows the suitability scores of each pond for each weight assignment.

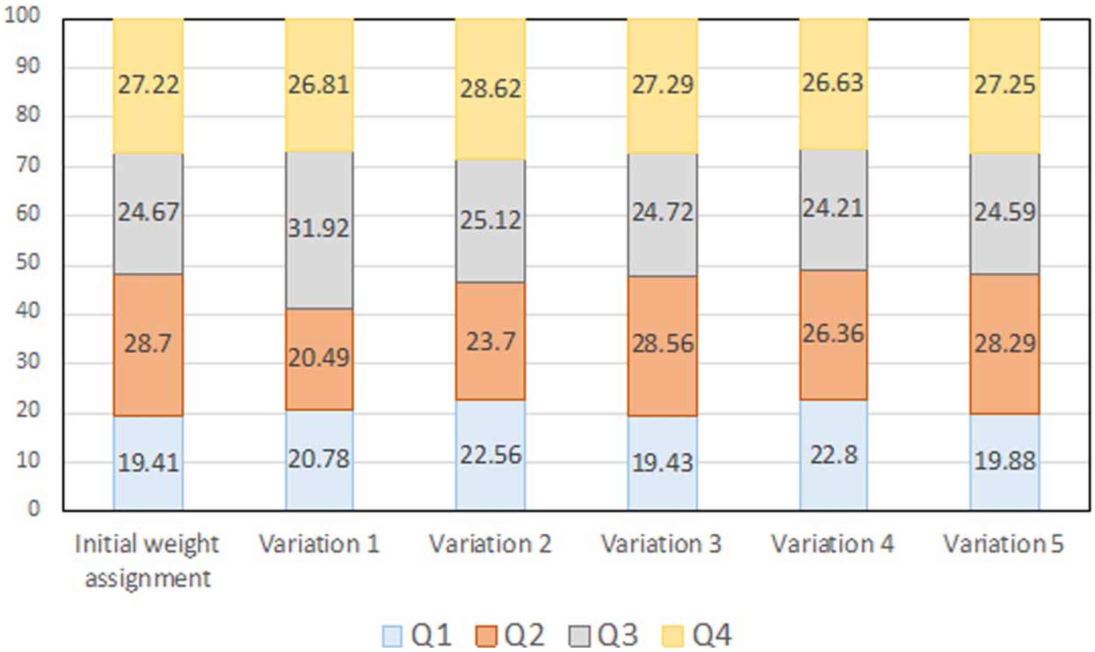

Figure 5 | Area covered (%) by each suitability quartile for each weight assignment.

In variation 1, where the distance from water bodies weight was higher, one *pokhari* laid in Q3 due to its proximity to a river, while all the other ponds were located in Q4 areas. The same occurred with another *pokhari* in the initial weight setting (the reason is addressed in the discussion).

Once we verified the robustness of the initial weight assignment, we proceeded with this preliminary map to obtain the final result. Considering the average suitability score of GPS points corresponding to existing *pokharis* and the standard deviation of all the different weight assignments (Table 4), the preliminary best-siting map can be considered successfully validated. The single suitability score of each point for each weight condition is reported in the Supplementary material.

In-field bio-geophysical data checking and participatory analysis

Kanchan Nepal members, together with local people, identified on the maps prepared for each location of interest some private lands. In the same maps, we also marked the location of terraces. These features, accounting for 3.18 km^2 (corresponding to 29% of high suitability areas within the four locations of interest in the preliminary map), were marked as unsuitable. It is important to note that the information on land ownership was not fully available for the whole study area.

Furthermore, we gathered information on both *pokharis*' characteristics and local knowledge criteria used to build these traditional ponds.

Local experts in *pokharis*' building explained that traditional criteria considered when locating new ponds are the following, ranked by importance:

- Accessibility (e.g. proximity to villages and roads or paths) – usually *pokharis* are built within 2 km from villages and as close as possible to tracks;
- Small flat areas where water stagnates over 4–5 years during monsoons.

Sometimes *pokharis* are built nearby small water springs which will feed the ponds themselves. Accessibility to *pokharis* is the most important criterion, as pond water is used mainly for cattle rearing and irrigation, which are activities carried out in areas surrounding the villages. Still for accessibility reasons, *pokharis* are located also near roads and tracks used by herders to move their cattle. *Pokharis*, especially in the past had also social functions, as people walking on mountain paths and carrying out daily activities used to rest near those ponds. Water stagnation during monsoons considered by indigenous knowledge supports our choice to include the upslope contributing area as best-siting criterion. We added these criteria to the preliminary bio-geophysical criteria set shown in Table 2. Creating our final socio-bio-geophysical criteria set. The upslope

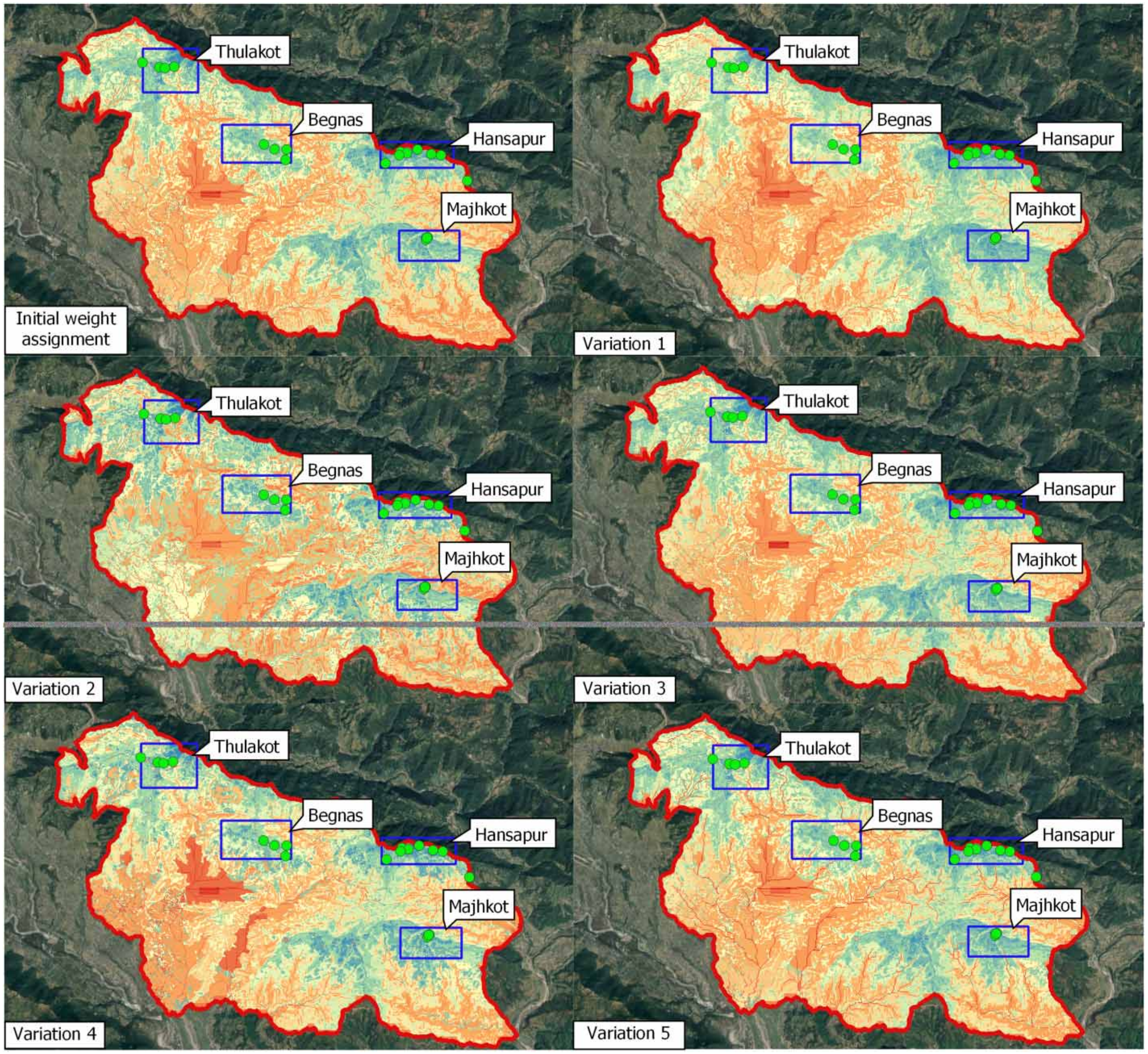

Figure 6 | Preliminary suitability maps obtained with the initial weight assignment and the five weight variations.

contributing area was already included in the MCDM analysis, we selected only Q4 suitable areas from the preliminary best-siting map and we removed those >2 km far from villages and those falling on private and terraced lands, which are unusable for community pond building, identified during the field visit.

Final best-siting map

The resulting final best sites map for *pokharis*' building is shown in Figure 8. Around 0.423 km^2 corresponding to 3.47% of the total area in the four focus zones (12 km^2) were found to be highly suitable, matching all the final socio-bio-geophysical criteria.

DISCUSSION

Pokharis' best-siting methodology

The main result of our study provides a first guidance for the identification and spread of potential sites for *pokharis* in Nepal. The sensitivity analysis confirms the robustness of our approach, which is also supported by the in-field validation. In fact,

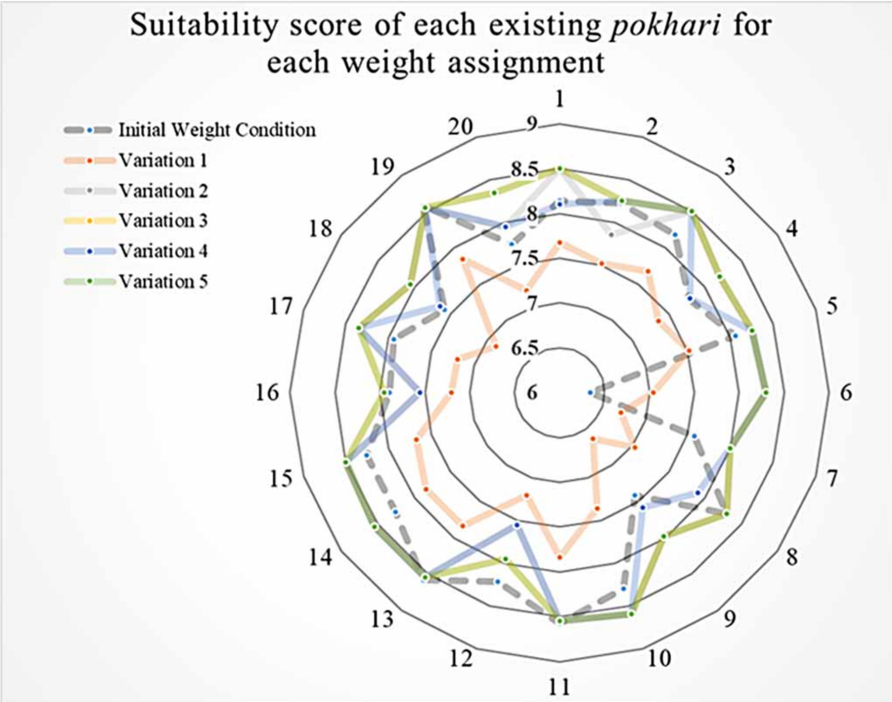

Figure 7 | Suitability score of each existing *pokhari* for each weight assignment displayed in a radar chart. Each radius of the circle represents one *pokhari*. The circles are relative to the suitability scores.

Table 4 | Average suitability score (*S*) and standard deviation of the six weight assignments

Weight assignment	Initial weight assignment	Variation 1	Variation 2	Variation 3	Variation 4	Variation 5
Mean *S*	8	7.36	8.23	8.31	8.15	8.31
Standard deviation	0.51	0.38	0.33	0.23	0.38	0.23

compared with other water harvesting best-siting analysis performed in other regions of the world, our results are among the ones with the highest correspondence between modelled sites and existing ones, with a 100% correspondence. The same percentage was obtained by Ramakrishnan *et al.* (2009) for ponds, while slightly lower accuracy was reported for other structures. Singhai *et al.* (2019) reported a suitability map accuracy of 90% with 31 surveyed farm ponds; Grum *et al.* (2016) validated check dams and percolation pond suitability, for these latter, an accuracy of 63% over 92 infiltration ponds is reported. In these studies, the number of existing structures is higher compared with our work, but the study areas are wider than ours. Moreover, the mentioned studies consider various WH structures and not just ponds as in our case. Our methodology also includes two rather uncommon criteria: upslope contributing area and elevation. This latter was introduced to prioritize higher altitude areas which are those more prone to water scarcity, while upslope contributing area was used to find minimum water accumulation potential, and it is consistent with traditional criteria reported by local experts. Moreover, the upslope contributing area can be easily computed from a DEM on GIS softwares compared with runoff estimation, which is more complicated and data-demanding.

Another key result of this study is the validated selection of siting criteria using participatory methods. We combined the benefits of an accurate validation with existing ponds with traditional knowledge to develop an efficient approach easily acceptable by local people and linked with their indigenous expertise. Other studies took into account traditional knowledge. For instance, Al-Adamat *et al.* (2012) asked local people to point out potential WH best sites on a map and to select some best-siting criteria like distance from roads, borders, villages, farmlands, and wells. Grum *et al.* (2016) also included a

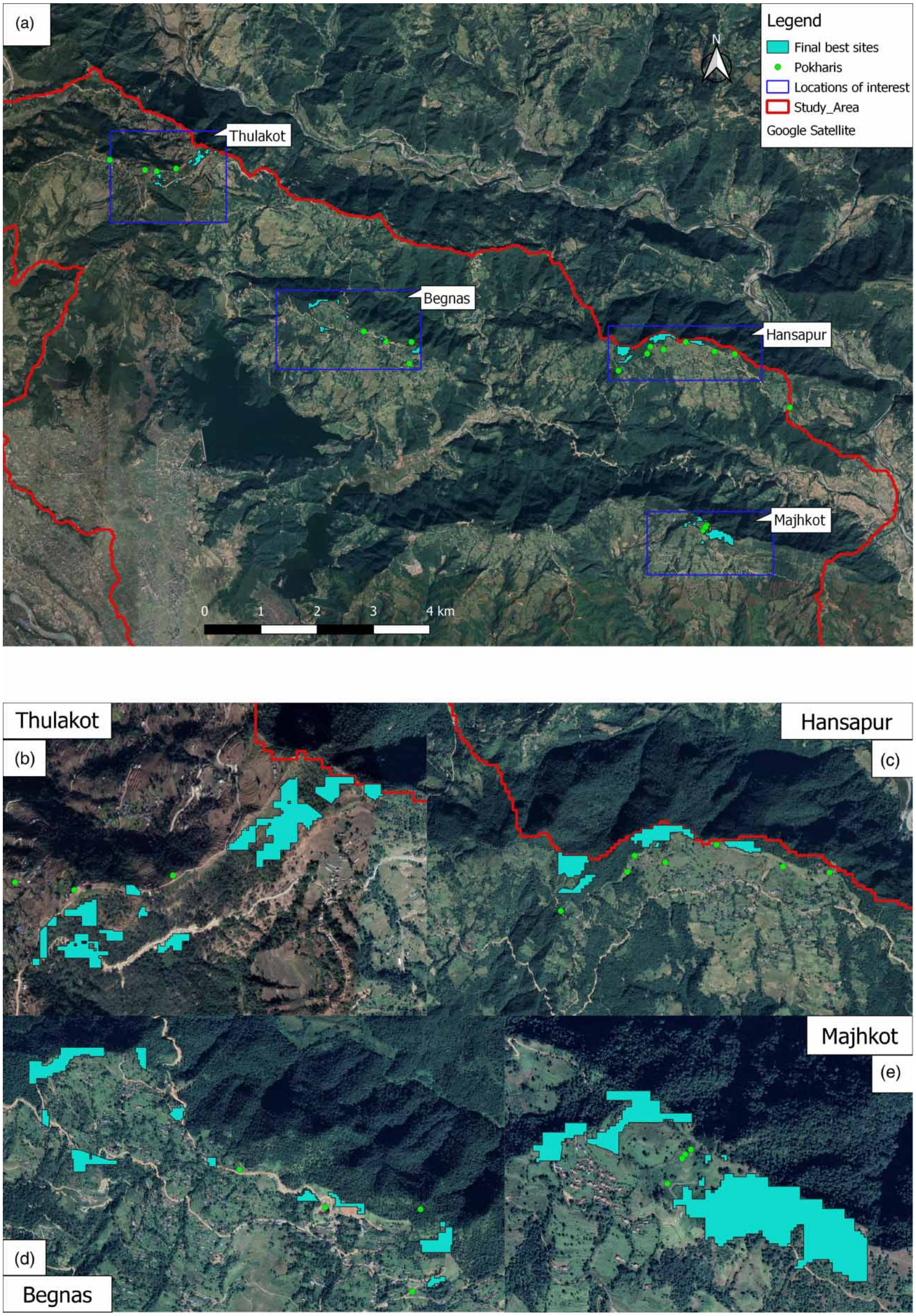

Figure 8 | Final best-siting map, including (a) the whole study area, (b) Thulakot area, (c) Hansapur area, (d) Begnas area, and (e) Majhkot area.

participatory approach to identify the most relevant criteria for local people in selecting the best WH techniques, and then they processed retrieved criteria with MCDM to sort out preferred water harvesting techniques. Finally, Mbilinyi *et al.* (2005) reported in their study carried out in Tanzania the traditional criteria used to locate new WH structures.

Concerning our comparison with traditional criteria, we added distance from villages as a socio-economic criterion pointed out by local people and upslope contributing area as a proxy for water stagnation points over years. We did not take into account springs, which was an additional indigenous criterion, as our analysis focused on rainwater storage.

Such a straightforward and validated approach for mapping best location of *pokharis* can immediately support government, NGOs and private efforts to build new distributed water points across Nepal. Increasing water available for farming, depending on the actual number of new structures and their size, can considerably improve the availability of water in the dry season, thus positively affecting both cattle health and agricultural productivity. Cascading impacts of increase water availability with *pokharis* might likely include increased food security and income stability, thus potentially reducing outmigration from rural areas, which is a pivotal cause of environmental degradation in Nepal (Pandey 2019). Other ecosystem services from *pokharis*, such as water retention and flood prevention, reduction of land erosion, cultural and social value would increase as well, improving people's wellbeing.

Main limitations

Our results report good correspondence between existing *pokharis*' locations and produced best-siting map. Thus, the presented method offers a useful guidance for WH structure best siting despite some limitations mainly due to data availability and quality. Regarding this latter issue, some considerations were made: the LULC layer was, despite being the best option available, unable to report the presence of terraces. These were reported instead as bareland or grassland (the best categories for pond building) leading to many suitable areas for pond construction. This problem was identified during the field visit and suitable areas were reduced as terraces are unsuitable for *pokhari* building. Terraced fields are usually private, and these limited lands often represent the main source of subsistence for farmers, thus it is not advisable to use those areas for community-owned ponds. Some techniques for terrace detection from remote sensing do exist (Tarolli & Sofia 2016), but the lack of high-resolution topographic data (1–2 m) hindered its estimation. Interestingly, the LULC reports the biggest *pokhari* as 'permanent water body', thanks to its good spatial resolution. Owing to this reason, the just mentioned *pokhari* is the one resulting in the third suitability quartile (see Supplementary material), because permanent water bodies were given the lowest suitability as they usually represent rivers or lakes. Actually, the water body in this case is the *pokhari* itself, thus the lower score is a 'false negative', i.e. an area resulting in a lower suitability score which, checking on the field, has instead a high suitability. This explains the 100% correspondence between retrieved best sites and existing structures despite one pond laying in the third quartile. The main limitation of the LULC map – for the scope of this work – lies in the broadness of the categories used in the classification. Particularly, pixels with a wood cover exceeding 10% are classified as tree cover even if 'other land cover classes can be present below the canopy, even with a density higher than trees' as stated in the ESA Worldcover Product User manual (Zanaga *et al.* 2021). The same occurs for grassland and shrubland. This affects our analysis as, for instance, open forests, which are very suitable, are not distinguished from closed forests, which are less suitable for WH structures having less free space. Despite being the best option available, the DEM is not ideal for best-siting analysis of relatively small structures, as in this case. A spatial resolution of 30 m cannot report small flat areas surrounded by steeper areas, which would be actually suitable for *pokharis*, especially in hilly/mountainous regions like Nepal. Also, data about land ownership were not available from institutions either before or during the field visit. However, local people provided information on some land property, which allowed us to exclude at least some private lands. Lastly, a digital map of housing was not available, so we had to remove areas too far from villages from the final best-siting map by visual inspection. The availability of a digital layer of settlements would have allowed the automatized integration of this traditional criteria into the GIS analysis, making this step faster and more accurate. Despite these limitations related to data availability and resolution, our methodology provides a first reliable guidance to large-scale planning of *pokharis*, with a good level of accuracy granted by the high validation standard and the integration with participatory methods. Particularly useful to overcome the quantitative data limitation was the integration of qualitative information from field inspection and participatory research. As in other studies (Castelli *et al.* 2018, 2021; Piemontese *et al.* 2021), the integration of indigenous knowledge was essential to (a) integrate the scarce data, (b) validate the overall approach and criteria, and (c) identify limitation and potential improvement for future work.

Further developments

With detailed soil and geological data, areas more prone to landslides (which in Nepal are common) could be estimated to remove suitable sites where water infiltration in soil could increase the risk of land collapse. This analysis could be done with the aforementioned high-resolution topography data if they will become available for Nepal too, as well as automated detection of terraces and small flat areas. Moreover, once new *pokharis* are built in at least some identified suitable spots, a thorough quantification of the benefits provided by these structures in terms of farm productivity and ecosystem services provision could be carried out. Furthermore, the proposed approach can be a guidance for similar works in other data-scarce areas with similar characteristics, to support decision-makers in sustainable land and water management and foster resilience to climate change.

CONCLUSION

We introduced a methodology for large-scale siting of traditional WH structures, which is consistent with traditional criteria. To our knowledge, it is the first best-siting analysis for Nepalese traditional ponds and one of the first best-siting works for Nepal. The best-siting analysis identified about 0.4 km^2 of highly suitable land for *pokharis*' construction, corresponding to 3.47% of the total location of interest's area covering around 12 km^2. As our analysis was successfully validated with a 100% agreement with existing *pokharis*, it can give decision-makers reliable guidance for water resources planning and management. Compared with the traditional siting methods focused on the local scale and individual structures, the combination of GIS and MCDM allows a fast and cost-effective best-siting analysis on wide areas, providing information that can support large-scale national to regional planning. Moreover, software and datasets used are freely available, so this analysis can be replicated by other institution or for other areas. Before building new structures, we recommend a field check, especially for land ownership and accessibility as this information is usually very difficult to retrieve remotely. Finally, the development of higher-resolution or better-quality datasets could improve the accuracy of our best-siting tool and improve the usefulness of our approach. The proposed methodology favours the prompt implementation of water harvesting techniques that, together with other soil and water conservation measures, can increase farming productivity through increased water availability for agriculture and livestock rearing.

ACKNOWLEDGEMENTS

This work was carried out in the framework of the project 'Rain Communities' carried out by the Swiss NGO International Rainwater Harvesting Alliance (IRHA) with its Nepalese partner NGO Kanchan Nepal. We would like to acknowledge the institutions funding the project, i.e. République et Canton de Genève, Puplinge and 1% fund. We would like to acknowledge also all the NGO members who supported us during the development of this work, especially concerning the field visit and all the villagers who collaborated with us during the participatory analysis.

The authors are thankful to editor and reviewers for evaluating and improving this manuscript.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

REFERENCES

Adham, A., Riksen, M., Ouessar, M. & Ritsema, C. 2016 Identification of suitable sites for rainwater harvesting structures in arid and semi-arid regions: a review. *Int. Soil Water Conserv. Res.* **4**, 108–120. https://doi.org/10.1016/j.iswcr.2016.03.001.

Adhikari, S. 2018 Drought impact and adaptation strategies in the mid-hill farming system of Western Nepal. *Environments* **5**, 101. https://doi.org/10.3390/environments5090101.

Adhikari, S. P., Timsina, K. P. & Lamichhane, J. 2018 Adoption and impact of rain water harvesting technology on rural livelihoods: the case of Makwanpur district, Nepal. *Rural Extension and Innovation Systems Journal* **14**(1), 34–40.

Al-Adamat, R., Diabat, A. & Shatnawi, G. 2010 Combining GIS with multicriteria decision making for siting water harvesting ponds in Northern Jordan. *J. Arid Environ.* **74**, 1471–1477. https://doi.org/10.1016/j.jaridenv.2010.07.001.

Al-Adamat, R., AlAyyash, S., Al-Amoush, H., Al-Meshan, O., Rawajfih, Z., Shdeifat, A., Al-Harahsheh, A. & Al-Farajat, M. 2012 The combination of indigenous knowledge and geo-informatics for water harvesting siting in the Jordanian Badia. *J. Geog. Inf. Syst.* **04**, 366–376. https://doi.org/10.4236/jgis.2012.44042.

Bastakoti, R. C., Prathapar, S. A. & Okwany, R. O. 2016 Community pond rehabilitation to deal with climate variability: a case study in Nepal Terai. *Water Resour. Rural Dev.* **7**, 20–35. https://doi.org/10.1016/j.wrr.2016.01.001.

Castelli, G., Bresci, E., Castelli, F., Hagos, E. Y. & Mehari, A. 2018 A participatory design approach for modernization of spate irrigation systems. *Agric. Water Manage.* **210**, 286–295. https://doi.org/10.1016/j.agwat.2018.08.030.

Castelli, G., Oo, W. M., di Maggio, A., Fellin, L., Re, V. & Bresci, E. 2021 Participatory analysis of sustainable land and water management practices for integrated rural development in Myanmar. *J. Water Sanit. Hyg. Dev.* **11**, 26–36. https://doi.org/10.2166/washdev.2020.166.

Chen, C., Meurk, C. D., Jia, Z., Lv, M., Wu, S. & Jia, J. 2017 Incorporating landscape connectivity into household pond configuration in a hilly agricultural landscape. *Landscapes Ecol. Eng.* **13**, 189–204. https://doi.org/10.1007/s11355-016-0317-3.

Chen, W., He, B., Nover, D., Lu, H., Liu, J., Sun, W. & Chen, W. 2019 Farm ponds in southern China: challenges and solutions for conserving a neglected wetland ecosystem. *Sci. Total Environ.* **659**, 1322–1334. https://doi.org/10.1016/j.scitotenv.2018.12.394.

de Winnaar, G., Jewitt, G. P. W. & Horan, M. 2007 A GIS-based approach for identifying potential runoff harvesting sites in the Thukela River basin, South Africa. *Phys. Chem. Earth Parts ABC* **32**, 1058–1067. https://doi.org/10.1016/j.pce.2007.07.009.

Dile, Y. T., Rockström, J. & Karlberg, L. 2016 Suitability of water harvesting in the Upper Blue Nile Basin, Ethiopia: a first step towards a mesoscale hydrological modeling framework. *Adv. Meteorol.* **2016**, 1–12. https://doi.org/10.1155/2016/5935430.

Grum, B., Hessel, R., Kessler, A., Woldearegay, K., Yazew, E., Ritsema, C. & Geissen, V. 2016 A decision support approach for the selection and implementation of water harvesting techniques in arid and semi-arid regions. *Agric. Water Manage.* **173**, 35–47. https://doi.org/10.1016/j.agwat.2016.04.018.

Japan Aerospace Exploration Agency (JAXA) 2021 *ALOS Global Digital Surface Model 'ALOS World 3D – 30 m (AW3D30)'. Version 3.2.* Available from: https://www.eorc.jaxa.jp/ALOS/en/dataset/aw3d30/aw3d30_e.htm (accessed 10 May 2021).

Krois, J. & Schulte, A. 2014 GIS-based multi-criteria evaluation to identify potential sites for soil and water conservation techniques in the Ronquillo watershed, northern Peru. *Appl. Geogr.* **51**, 131–142. https://doi.org/10.1016/j.apgeog.2014.04.006.

Lal, C. & Verma, L. R. 2008 Indigenous Technological Knowledge on Soil and Water Management From Himachal Himalaya, vol. 7, p. 9.

Márquez, J. D., Peña, L. E., Barrios, M. & Leal, J. 2021 Detection of rainwater harvesting ponds by matching terrain attributes with hydrologic response. *J. Cleaner Prod.* **296**, 126520. https://doi.org/10.1016/j.jclepro.2021.126520.

Mbilinyi, B. P., Tumbo, S. D., Mahoo, H. F., Senkondo, E. M. & Hatibu, N. 2005 Indigenous knowledge as decision support tool in rainwater harvesting. *Phys. Chem. Earth Parts ABC* **30**, 792–798. https://doi.org/10.1016/j.pce.2005.08.022.

Mbilinyi, B. P., Tumbo, S. D., Mahoo, H. F. & Mkiramwinyi, F. O. 2007 GIS-based decision support system for identifying potential sites for rainwater harvesting. *Phys. Chem. Earth Parts ABC* **32**, 1074–1081. https://doi.org/10.1016/j.pce.2007.07.014.

Mugo, G. M. & Odera, P. A. 2019 Site selection for rainwater harvesting structures in Kiambu County-Kenya, Egypt. *J. Remote Sens. Space Sci.* **22**, 155–164. https://doi.org/10.1016/j.ejrs.2018.05.003.

Nepalese National Soil Science Research Center (NARC) website. Available from: https://soil.narc.gov.np/soil/soilmap/ (accessed 21 May 2021).

Pandey, R. 2019 Farmers' perception on agro-ecological implications of climate change in the Middle-Mountains of Nepal: a case of Lumle Village, Kaski. *Environ. Dev. Sustain.* **21**, 221–247. https://doi.org/10.1007/s10668-017-0031-9.

Piemontese, L., Kamugisha, R. N., Tukahirwa, J. M. B., Tengberg, A., Pedde, S. & Jaramillo, F. 2021 Barriers to scaling sustainable land and water management in Uganda: a cross-scale archetype approach. *Ecol. Soc.* **26**, art6. https://doi.org/10.5751/ES-12531-260306.

Ramakrishnan, D., Bandyopadhyay, A. & Kusuma, K. N. 2009 SCS-CN and GIS-based approach for identifying potential water harvesting sites in the Kali Watershed, Mahi River Basin, India. *J. Earth Syst. Sci.* **118**, 355–368. https://doi.org/10.1007/s12040-009-0034-5.

Singhai, A., Das, S., Kadam, A. K., Shukla, J. P., Bundela, D. S. & Kalashetty, M. 2019 GIS-based multi-criteria approach for identification of rainwater harvesting zones in upper Betwa sub-basin of Madhya Pradesh, India. *Environ. Dev. Sustain.* **21**, 777–797. https://doi.org/10.1007/s10668-017-0060-4.

Subedi, A., Kalauni, D., Khadka, R. & Kattel, R. R. 2020 Assessment of role of water harvesting technology in vegetable-based income diversification in Palpa district, Nepal. *Cogent Food Agric.* **6**, 1758374. https://doi.org/10.1080/23311932.2020.1758374.

Tarolli, P. & Sofia, G. 2016 Human topographic signatures and derived geomorphic processes across landscapes. *Geomorphology* **255**, 140–161. https://doi.org/10.1016/j.geomorph.2015.12.007.

United Nations Development Programme (UNDP) 2020 *Human Development Report 2020*. Available from: http://hdr.undp.org/en/2020-report (accessed 20 October 2021).

Ward, M., Poleacovschi, C. & Perez, M. 2021 Using AHP and spatial analysis to determine water surface storage suitability in Cambodia. *Water* **13**, 367. https://doi.org/10.3390/w13030367.

Zanaga, D., Van De Kerchove, R., De Keersmaecker, W., Souverijns, N., Brockmann, C., Quast, R., Wevers, J., Grosu, A., Paccini, A., Vergnaud, S., Cartus, O., Santoro, M., Fritz, S., Georgieva, I., Lesiv, M., Carter, S., Herold, M., Li, L., Tsendbazar, N. E., Ramoino, F. & Arino, O. 2021 *ESA WorldCover 10m 2020 v100*. https://doi.org/10.5281/zenodo.5571936 (accessed 5 October 2021).

First received 15 February 2022; accepted in revised form 16 September 2022. Available online 5 October 2022