

A Spatial Multi-Criteria Analysis Approach for Locating Suitable Sites for Construction of Subsurface Dams in Northern Pakistan

Imran Ali Jamali · Ulla Mörtberg · Bo Olofsson ·
Muhammad Shafique

Received: 15 May 2014 / Accepted: 15 September 2014 /
Published online: 23 September 2014
© Springer Science+Business Media Dordrecht 2014

Abstract Pakistan is an agricultural country with an increasing interest for hydropower. Water management problems such as sedimentation and evaporation have been of high concern for surface water reservoirs for many years. Therefore, groundwater storage through subsurface dams could be promising, especially considering the monsoon rainfall and seasonal river flows in Pakistan. The paper aims to develop and test a methodology to locate suitable sites for construction of subsurface dams using spatial multi-criteria analysis (SMCA) in the northern parts of Pakistan. For the study, spatial data on geology, slope, land cover, soil depth and topographic wetness index (TWI) was used. Two weighting techniques, i.e. the analytic hierarchy process (AHP) and the factor interaction method (FIM), were employed and compared. The sensitivity of the two methods as well as of the model parameters was analysed. The suitability map derived from AHP yielded about 3 % (16 km²) of the total area as most suitable, about 4 % (22 km²) as moderately suitable and about 0.8 % (5 km²) as least suitable. The suitability map derived from FIM identified about 2.7 % (14 km²) of the total area as most suitable, about 4 % (22 km²) as moderately suitable and about 1 % (7 km²) as least suitable. The sensitivity analyses suggested that AHP was a more robust weighting technique than FIM and that land cover was the most sensitive factor. The methodology presented here shows promising results and could be used in early planning to locate suitable sites for construction of subsurface dams.

Keywords Subsurface dams · Pakistan · Groundwater · Spatial multi-criteria analysis · AHP · GIS

1 Introduction

Improved water supply and water resources management is considered to boost economic development and to contribute significantly to poverty alleviation. According to Shiklomanov

I. A. Jamali (✉) · U. Mörtberg · B. Olofsson
Department of Sustainable Development, Environmental Science and Engineering, KTH Royal Institute of
Technology, 100 44 Stockholm, Sweden
e-mail: ialj@kth.se

M. Shafique
National Center of Excellence in Geology, University of Peshawar, Peshawar, Pakistan

(1999), global economies are highly dependent on rainfall variability; and there is a positive correlation between water storage capacity and economic growth. About 66 % of the global water withdrawal is used for the agriculture sector which rises to 90 % in arid regions (Shiklomanov 1999). Therefore, water scarcity may lead to food supply problems, especially in low income countries (UN Water Work Programme 2010–2011).

Pakistan is an agricultural country where the agriculture sector contributes to half of the country's employment, 24 % of GDP and about 70 % of the exports (Pakistan Bureau of Statistics 2012). Thus, water issues are high on the national agenda. Furthermore, the population of Pakistan is growing at 3 % per year which puts immense pressure on water resources which are already depleting (Ahmad et al. 2004). The climate of Pakistan is, however, generally arid and semi-arid. The central and southern parts (about two-thirds of the total area) have an annual rainfall of less than 250 mm. Only a small belt in the northern mountainous range displays humid conditions where rainfall could be as high as 750 mm. Since more than 80 % of the annual flows are received in the summer monsoon season, river flows are highly seasonal (Pakistan Meteorological Department 2011).

The strong dependency on agriculture has resulted in the development of a large network of irrigation systems based on surface water reservoirs. The Indus Basin irrigation system of Pakistan also claims to be the world's largest system (USAID 2009). However, sedimentation of the surface water reservoirs has been a concern in Pakistan for many years. Two of Pakistan's major dams called the Tarbela and Mangla reservoirs have lost storage capacity by up to 30 % and 20 % respectively due to sedimentation (Haq and Abbas 2006). After the Tarbela dam was constructed in 1976, there has not been any major addition to surface water storage capacity. Annual evaporation losses in Pakistan are estimated to be 20 % from surface water reservoirs (Ahmad 1982).

Due to the vulnerability of surface reservoirs, most of the agriculture and domestic demands, especially in the most populous province of Punjab, are met with groundwater. In other provinces, the trend of using groundwater is increasing as well (Qureshi et al. 2010). As a result of over-exploitation, groundwater levels are depleting and salinity levels in coastal areas are increasing because of saltwater intrusion. Besides water problems, the country is also facing an energy crisis and the most feasible source of energy is considered to be hydropower (Kessides 2013; Mirza et al. 2008). In face of the complexity of these issues, Bazilian et al. (2011) suggested an integrated approach for considering the sustainability of the energy, water and food nexus by policy makers in developing countries.

In the regions with monsoon season, rainfall often comes in quick showers and usually is followed by long dry periods. Therefore, rainwater needs to be harvested to counter water shortage during dry periods (Raju et al. 2006). Rainwater harvesting (RWH) techniques could potentially be used to artificially recharge groundwater aquifers and fill exhausted reservoirs (Ali 2010; Dhakate et al. 2013; Ibrahim 2009). Natural groundwater storage can be enhanced by constructing a subsurface barrier, i.e. a subsurface dam, to arrest the subsurface flows in the sediment layers (Nilsson 1988). Subsurface dams consist of a physical barrier (bentonite, clay, concrete, grout and/or sheet piles) constructed underground to block the groundwater flows and raise the water table levels in natural aquifers. These dams are usually 3–10 m deep and are often constructed across a wide valley with gentle gradient, consisting of aquifers of even thickness, which drains through a narrow passage between outcroppings. It is important that there is no or minimum vertical and lateral flow of groundwater behind the barrier, i.e. the bedrock is nearly impermeable. The crest of the dam is often kept about 0.5–1 m below the ground surface to allow some groundwater flow downstream and to prevent water logging upstream (Nilsson 1988).

Thus, subsurface dams seem to constitute an effective way of increasing groundwater storage (Jamali et al. 2013). Groundwater storage has many advantages over surface water

storage, i.e. negligible evaporation, no submergence of valuable land and generally lower microbiologically contamination concerns. In line with this, Baurne (1984) made a comparative study on surface water storage with groundwater storage and found the latter quite sustainable and economically feasible. In addition, such dams can prevent saltwater intrusion and can increase safe yields to a significant level in coastal areas (Anwar 1983; Sugio et al. 1987).

Subsurface dams proved to be quite sustainable in various parts of the world with very few reported environmental impacts. Ishida et al. (2011) described such dams in various countries, i.e. Japan, India, Ethiopia, Burkina-Faso, Kenya, South Korea, China, Brazil and USA. Raju et al. (2006) reported on the construction of four subsurface dams in 2001–2002 across the river Swarnamukhi basin in India. They concluded that there was a significant increase in groundwater storage after the dam construction which has led to improvements of the agriculture in the area. Moreover, subsurface dams do not need much maintenance, if any, and their functionality could be monitored through observation wells. In Pakistan there is no (to best of our knowledge) reported existence of naturally recharging artificially constructed groundwater storage, though several studies have been conducted particularly in the southwestern province of Balochistan for groundwater storage (Bhatti et al. 2008; Hendrickx et al. 1991; Qureshi et al. 2010; Suleman et al. 1995). According to their findings, the region has high potential for groundwater storage. Therefore, groundwater storage through subsurface dams seems promising considering the monsoon rainfall and seasonal river flows in Pakistan. Storage of fresh water in aquifers will also afford an additional benefit of reducing seawater intrusion. Moreover, these dams can also delay groundwater flow and, thus, can minimize the intensity of floods which have been quite frequent in Pakistan in recent years (Tariq and van de Giesen 2012).

There are, nevertheless, several examples of subsurface dams which have not been successful due to lack of planning and not being located in suitable sites (Nilsson 1988). Locating suitable sites for construction of subsurface dams requires detailed field investigations and integration of multiple physical and socio-economic factors (Jamali et al. 2013; Nilsson 1988). However, for early planning stages, spatial multi-criteria analysis (SMCA) where GIS plays a role in analysing spatial data and MCA provides procedures to structure decision problems; can provide an efficient decision support tool for water resources management; through identifying potential sites for a specific purpose, using commonly available datasets (Chenini et al. 2010; Graymore et al. 2009; Malczewski 2004).

Several authors have adopted SMCA for locating suitable sites for RWH and groundwater recharge using factors such as topography, geology, land cover, hydrology and hydrogeology (Al-Adamat et al. 2010; Jha et al. 2014; Machiwal et al. 2011; Rahman et al. 2013, 2012). MCA problems often involve criteria of varying importance; therefore, information about the relative importance of the criteria is needed. This is achieved by assigning a weight to each criterion. There are a number of weighting techniques available in the literature, depending upon the judgements of experts, stakeholders or decision makers (Malczewski 1999). Al-Adamat et al. 2010 and Mukherjee et al. (2012) followed a direct weighting approach for criteria justification based on scientific knowledge for locating water harvesting ponds and groundwater potential zones. Rahman et al. (2012, 2013) followed the analytic hierarchy process (AHP) and direct weighting approaches for modelling managed aquifer recharge site suitability. Jha et al. (2014) used AHP weighting techniques in their SMCA approach for identifying potential sites for RWH structures. Moreover Shaban et al. (2001) followed by Kourgialas and Karatzas (2011) introduced a factor interaction method (FIM) as a weighting technique. FIM is based on the idea that the importance of any physical factor cannot be evaluated individually but rather those factors can increase or decrease the influence on the

output when integrated. For sustainable planning of subsurface dams, their localisation needs to be based on scientific knowledge and, if not available, expert judgment. In order to synthesise and apply existing scientific knowledge and/or expert judgment in the decision problem, suitable decision making tools are called for.

The aim and novelty of this paper was to develop a methodology for locating suitable sites for the construction of subsurface dams in northern Pakistan using SMCA. Moreover, specific aims were to test and compare two weighting techniques, i.e. AHP and FIM, for structuring the decision problem and to identify the most important physical factors which need to be considered for localization of such dams. Criteria for selecting suitable sites were based on topographical, geological, soil depth and land cover data. Since the method is based on commonly available digital data, it was intended to be replicable in other terrains with comparable geological and hydrological conditions.

2 Materials and Methods

2.1 Study Area

The study for locating suitable sites for the construction of subsurface dams was carried out within an area of about 516 km² in northern Pakistan embracing the cities of Muzaffarabad, Gari Habib Ullah and Balakot and surrounding areas (Fig. 1). The study area has a rough terrain where the elevation ranges from 608 to 3,789 m above mean sea level with terrain gradients from flat to as steep as 65°. Geologically, the study area is covered by 11 formations

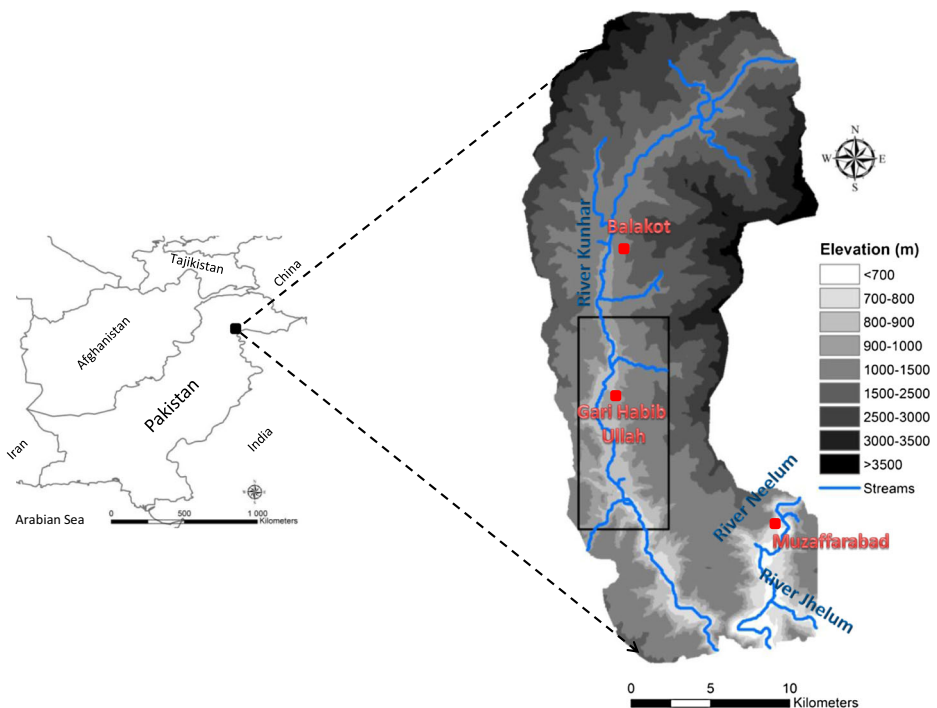


Fig. 1 Location and elevation of the study area. The *rectangle* shows the focus area used for discussion

(Hussain et al. 2004; Latif et al. 2008) with different lithologies (Fig. 2a and Table 1). The area is mainly covered by sedimentary rocks predominantly composed of highly fractured sandstone, limestone and shale (Hussain et al. 2004; Kamp et al. 2008; Latif et al. 2008). The easily erodible nature of these rocks and the rough terrain of the study area have resulted in weathering and erosion forming quaternary deposits by the steep cliffs along the streams. The quaternary deposits consist of alluvium and colluvium sediments. Alluvium deposits include boulders, cobbles, gravel, sand and silt which could be up to 3 m thick overlaying the bedrock of different ages. Colluvium deposits are formed from the weathered Muzaffarabad, Murree and Hazara formations and accumulate at the base of slopes due to gravity and slope processes.

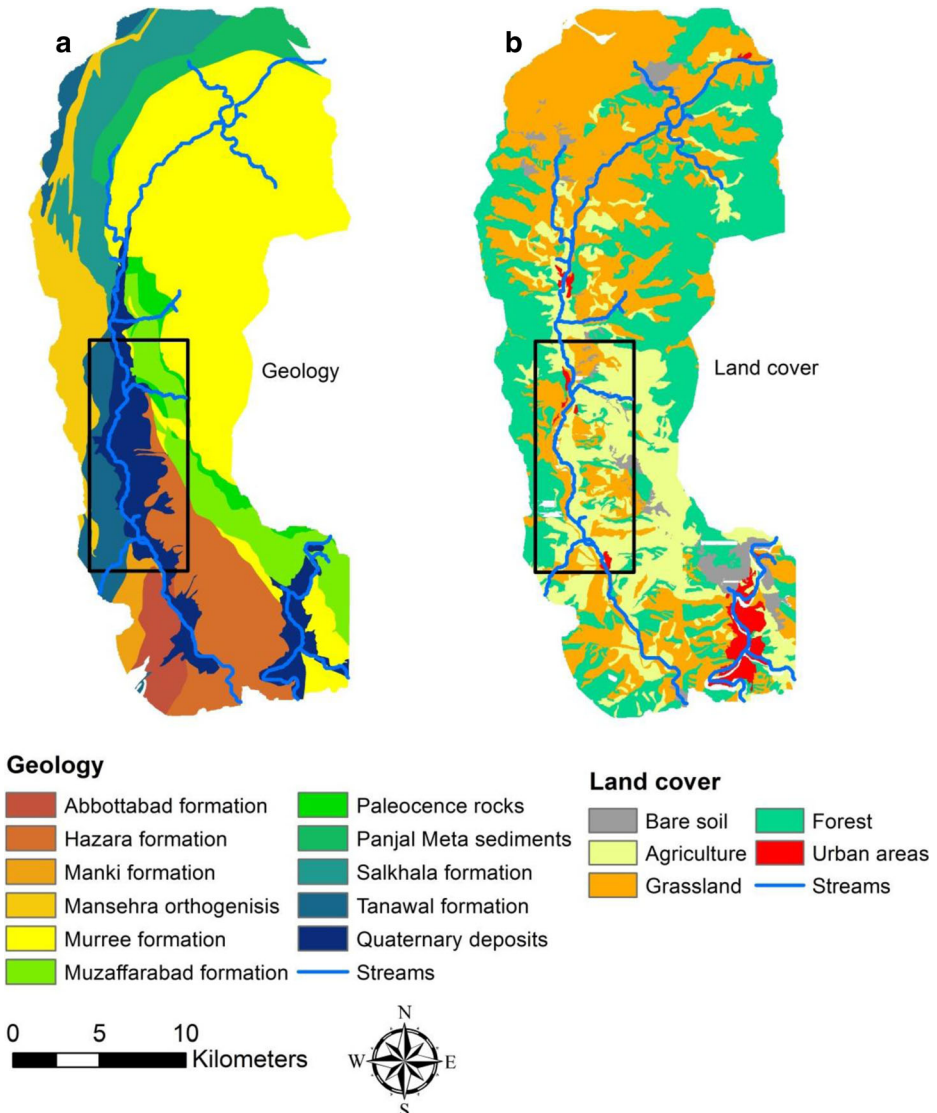


Fig. 2 Geological and land cover maps of the study area. The *rectangle* shows the focus area used for discussion

Table 1 Lithologies of the different geological formations within the study area (after Basharat et al. 2012; Hussain et al. 2004; Kamp et al. 2008; Latif et al. 2008)

Formation	Lithology
Abbotabad formation	Sandstone, limestone, chert dolomite bands and pure dolomite bands
Hazara formation	Slate, phyllite, metasandstone, shale, siltstone, limestone and graphitic layers
Manki formation	Slate and phyllitic slate with subordinate interactions of quartzite and limestone
Manshehra orthogneiss	Phyllite and coarse grained two-mica granite gneiss
Murree formation	Interbedded sandstone, siltstone, mudstone, shale and claystone
Muzaffarabad formation	The cherty and stromatolitic dolomite, cherty white and grey bands, limestone and black shale
Paleocene rocks	Limestone, shale
Panjal metasediments	Metacarbonates, metasediments, metavolcanics, quartzite and graphitic schist
Salkhala formation	Phyllite, schist, limestone and quartzite
Tanawal formation	Pelitic, psammitic metasedimentary rocks with local subordinate graphitic schist, talc schist and marble
Quaternary deposits	Alluvium and colluvium

The study area is covered by forest (35 %), grassland (38 %), agricultural land (21 %), urban areas (2 %) and bare soil (4 %) and is vulnerable to natural disasters such as floods, landslides and earthquakes (Fig. 2b). This region was severely devastated by 2005 year's Kashmir earthquake and 2010 year's floods that also triggered thousands of landslides. The study area is drained by the Kunhar, Jhelum and Neelum rivers (Fig. 1). The climate of the area is monsoonal with an annual precipitation of 1,500 mm at Muzaffarabad (DCR 1998). There are two seasons with rainfall in Pakistan: the monsoon (occurring between July and September) with about one-third of the rain falling during July and August and the Western Depression (takes place between December and March) (Pakistan Meteorological Department 2011). In winter precipitation takes the form of snow, especially over the mountain ranges, that becomes a source of water during the summer (DCR 1998). The high temperature from June to August triggers the melting of snow; accompanied by the monsoon rain; significantly increasing the river discharges, which often leads to flooding. For example, the river flow at Gari Habib Ullah (Fig. 1) increases from $20 \text{ m}^3\text{s}^{-1}$ in January to $180 \text{ m}^3\text{s}^{-1}$ in July, resulting in downstream flooding (Scallly 1994). Moreover the evapotranspiration rates are also quite high in summer time in these areas (DCR 1998).

2.2 Data

Spatial data used for the analysis included a Digital Elevation Model (DEM) in raster format of 30 m horizontal resolution which was obtained from the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) data (ASTER 2009). Geological data in vector format was obtained from the Geological Survey of Pakistan (GSP 2009) and land cover data was obtained from Shafique et al. (2011b) which they derived from satellite images.

2.3 Deriving Criteria

To identify potentially suitable locations for subsurface dams, SMCA was applied, where the criteria consisted of either constraints, i.e. criteria that represented unsuitable areas, or factors, i.e. criteria that were considered to enhance the suitability for the location of such dams. For

the SMCA, the initial processing of data as well as visualisation of the final results was done in ArcGIS (ESRI 2013). IDRISI Andes (Eastman 2006) was used to combine constraints and factors into suitability maps.

In this study, two types of constraints derived from geology and land cover data were applied. Boolean criteria were used to eliminate the areas where subsurface dams would not be suitable to build, which means that the criteria can be either true or false by designation of a binary number, 1, including; or 0, excluding (Eastman 1999). Thus, a constraint map was generated from the geological data of the study area (Table 1 and Fig. 2a), where quaternary deposits were assigned a value of 1 and all other classes were assigned the value 0. Likewise, a constraint map was derived from the land cover data where urban areas were assigned the value 0 and all other classes were assigned the value 1 (Fig. 2b).

Factors that were considered in the SMCA were land cover data, in categorical form, and slope, soil depth and TWI, in quantitative form (Table 2). From the DEM, the slope data was derived and a topographic wetness index (TWI) was calculated. TWI is commonly used to quantify topographic control on hydrological processes, whereas a higher value of TWI implies more upslope drainage area through a particular point and vice versa (Beven and Kirkby 1979; Quinn et al. 1995). In order to estimate the depth to bedrock, a regolith thickness model developed by Shafique et al. (2011a) for this study area was used.

For standardisation of the factors, fuzzy membership functions were used, where the factors were standardised using fuzzy sets to a scale of 0–255 where 0 was not suitable and 255 was most suitable. Fuzzy sets are sets without sharp boundaries so that the transition between membership and non-membership of a location in the set is gradual, following different membership functions (Eastman 2006). The fuzzy membership function types and shapes adopted for the different factors were mainly based on scientific knowledge and expert judgement (Table 2 and Fig. 3). However, for TWI neither was available, therefore, a comparative analysis was performed in order to compare land cover class frequency with TWI for this particular study area and to derive meaningful inflection points for the fuzzy membership function.

Table 2 Factors used in the SMCA

Factor	Class range/description	Fuzzy membership function	Fuzzy membership function shape	Motivation for fuzzy membership type and shape
Soil depth (m)	0–24	Sigmoidal	Symmetric	(Ishida et al. 2006; Raju et al. 2006; Ministry of the environment Japan 2004).
Slope (%)	0–103	Sigmoidal	Monotonically decreasing	(Nilsson 1988).
Land cover (classes)	Bare soil (1)* Grassland (2)* Agriculture (3)* Forests (4)*	Sigmoidal	Monotonically decreasing	Expert judgment
TWI (index)	0–26	J-shaped	Monotonically increasing	Statistical analysis of ranges of TWI in different land cover classes

*Land cover classes were ranked (1–4), corresponding to suitability for subsurface dams, to convert them from categorical form to quantitative form to be able to use these numbers as inflection points in a fuzzy membership function

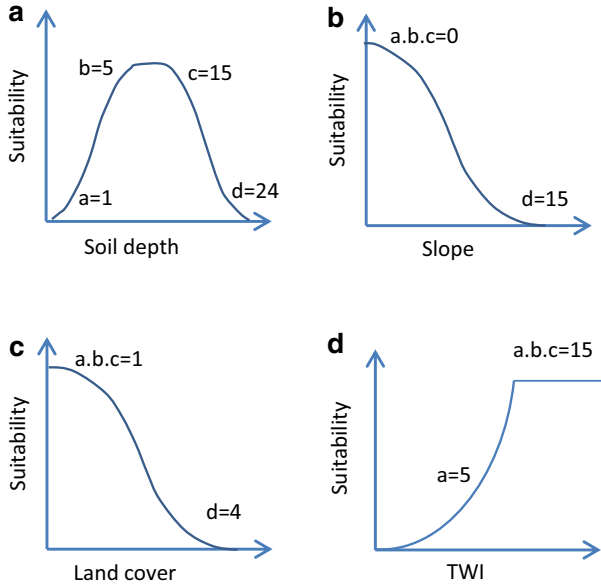


Fig. 3 Fuzzy membership functions adopted for the different factors in the SMCA. The *a, b, c* and *d* values show the inflection points for different fuzzy membership function shapes

2.4 Approaches to Weighting of Criteria

One of the important steps in SMCA is combining its main elements using decision rules that provide a basis for ordering the decision alternatives and choosing the most preferred alternative (Malczewski 1999, 2000). While the constraints were treated with a Boolean approach, the factors were treated with weighted linear combination (WLC) decision rules. WLC involves standardization of suitability maps, assigning weights of relative importance to them and combination of standardized maps and weights to get an overall suitability score (Ayalew and Yamagishi 2005). WLC can be expressed as Eq. 1:

$$A_i = \sum_j w_i \cdot x_{ij} \tag{1}$$

where A_i is the final suitability score in each pixel, x_{ij} is the suitability of the i th cell with respect to the j th layer, and w_i is the normalized weight so that $\sum w_i = 1$.

The next step in the SMCA was to assign weights to each factor. Two weighting techniques, i.e. AHP and FIM, were employed and compared in this paper. The AHP approach is based on three principles such as decomposition, comparative judgement and synthesis of priorities (Malczewski 1999; Saaty 1980). This method takes a pairwise comparison as an input using a point scale to express individual judgments when comparing each pair of factors (Fernández and Lutz 2010; Saaty 1980). It produced relative weights as output, thus creating a ratio matrix, which was checked for consistency according to standard AHP methodology (Anbazhagan et al. 2012; Fernández and Lutz 2010; Malczewski 1999; Saaty 1980).

The FIM approach was presented by Shaban et al. (2001) and Kourgialas and Karatzas (2011) and it is based on the idea that the importance of any physical factor cannot be evaluated individually; rather the factors can increase or decrease the

influence on the output when integrated. To this end, a factor interaction scheme (based on scientific knowledge and expert judgement) was prepared to analyse the influence of one factor over others (Fig. 4). In FIM, for a major effect (solid line), ten points, for a minor effect (dashed line), 5 points whereas for no effect, no point was assigned to the factors. Slope was the most influential factor which had two major effects, i.e. soil depth and TWI, and one minor effect, i.e. land cover, which assigned it a total score of 25 (Fig. 4b). Similarly scores for all other factors were calculated. Factor scores were summed and the total was obtained. Percentage weight for each factor was obtained by dividing its individual score with the total score.

Two suitability maps were obtained using two sets of weights, derived from AHP and FIM, respectively. The resulting suitability maps were reclassified into three classes; most suitable, moderately suitable and least suitable using natural breaks (Jenks). Two sensitivity analyses were applied, i.e. for evaluating the stability of the weighting techniques and for analysing the importance of the factors on the output. In order to explore the robustness of the weighting techniques, a sensitivity analysis was performed (Qureshi et al. 1999) by reducing the weights of one factor by 50 % and distributing the equivalent weights equally over the other factors and analysing the variation in the output maps. Furthermore, in order to make an evaluation of which factor would be the most sensitive, a factor removal approach was applied (Babiker et al. 2005; Lodwick et al. 1990). To this end factors were integrated using equal weights first and then one factor was removed at a time to see the variation in the output suitability maps.

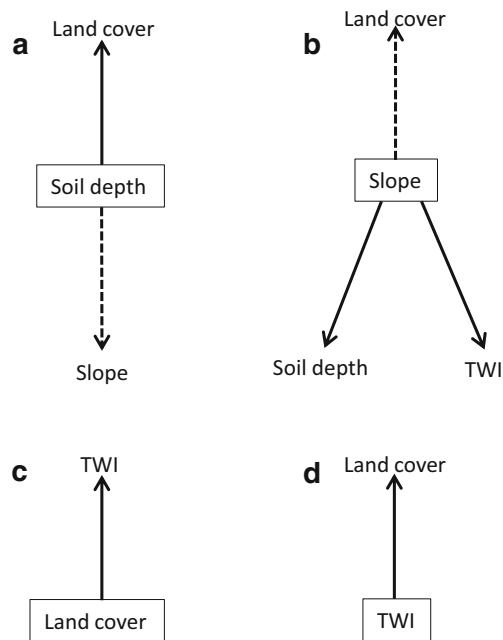


Fig. 4 A schematic description of FIM showing the assumed interaction between the factors, i.e. **a** soil depth **b** slope **c** land cover **d** TWI, which increase or decrease the influence on the output when integrated for the selection of suitable sites for construction of a subsurface dam. *Solid lines* illustrate a major effect of one factor over other, whereas the *dotted lines* illustrate a minor effect

3 Results and Discussion

In order to enable the use of TWI as a factor, a comparative analysis between land cover data and TWI for the study area was performed (Fig. 5). From this analysis, the inflection points for the fuzzy membership function of this factor were derived. For constructing subsurface dams, higher TWI values were considered to be suitable (Jamali et al. 2013). However, a motivation was established for choosing an appropriate fuzzy membership type and shape for TWI. It was suggested from the results of the analysis that the mean TWI value for all the land cover classes was about 9 with a minimum of 5. Agriculture, however, had the longest stretch covering all the range of TWI values up to 26. Therefore, a fuzzy membership J-shape type was chosen with monotonically increasing shape, where 5 and 15 were considered as inflection points (Table 2 and Fig. 3d). This suggested that the suitability increased gradually from 5 to 15 for the TWI values, thereafter from 15 to 26, suitability was considered to be the same. The application of the four factors that were used for the SMCA (Table 2), in a focal part of the study area, is illustrated in Fig. 6a–d. These factor maps illustrate different patterns of suitability but the most suitable areas in all the maps were concentrated in the central parts. In this study two types of constraints, derived from geology and land cover data, were considered (Fig. 6e–f). The geological constraint that eliminated rock areas omitted large parts of the study area. Likewise, Nilsson (1988) suggested that the most suitable geological formations for construction of subsurface dams are river beds consisting of sand and gravel deposits with a bearing capacity ranging from 5 to 50 %. However, subsurface dams have been constructed in limestone aquifers in Japan and in clay, silt and sand aquifers in Burkina-Faso (Ishida et al. 2006; Ministry of the environment Japan 2004; Raju et al. 2006). The rock outcrops within the current study area have though a very small storage capacity. The geological formations around the Kunhar, Neelum and Jhelum rivers consist of quaternary sediments (Basharat et al. 2012; Shafique et al. 2011b). Therefore, quaternary deposits were considered suitable for the construction of subsurface dams, while the rock formations were not.

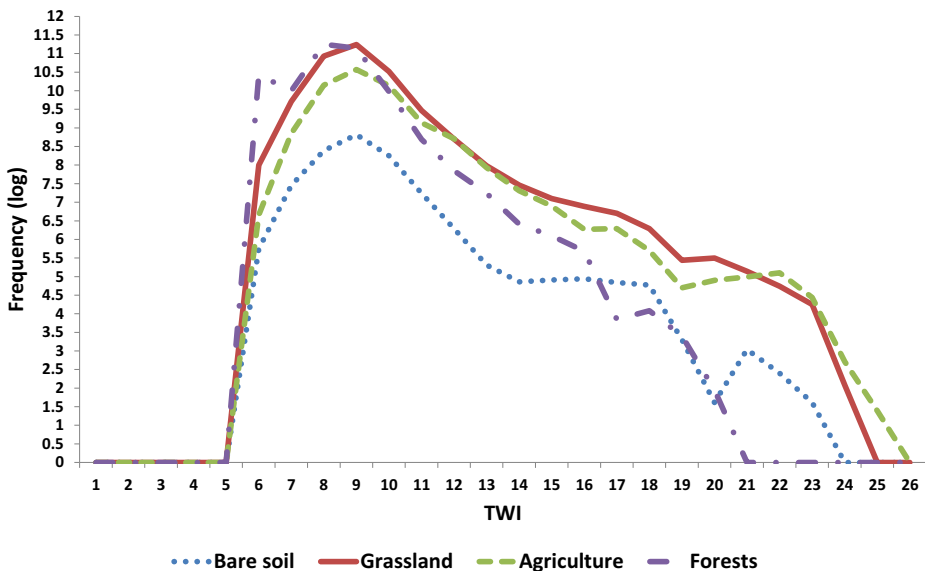


Fig. 5 The range of the TWI values in relation to each land cover class

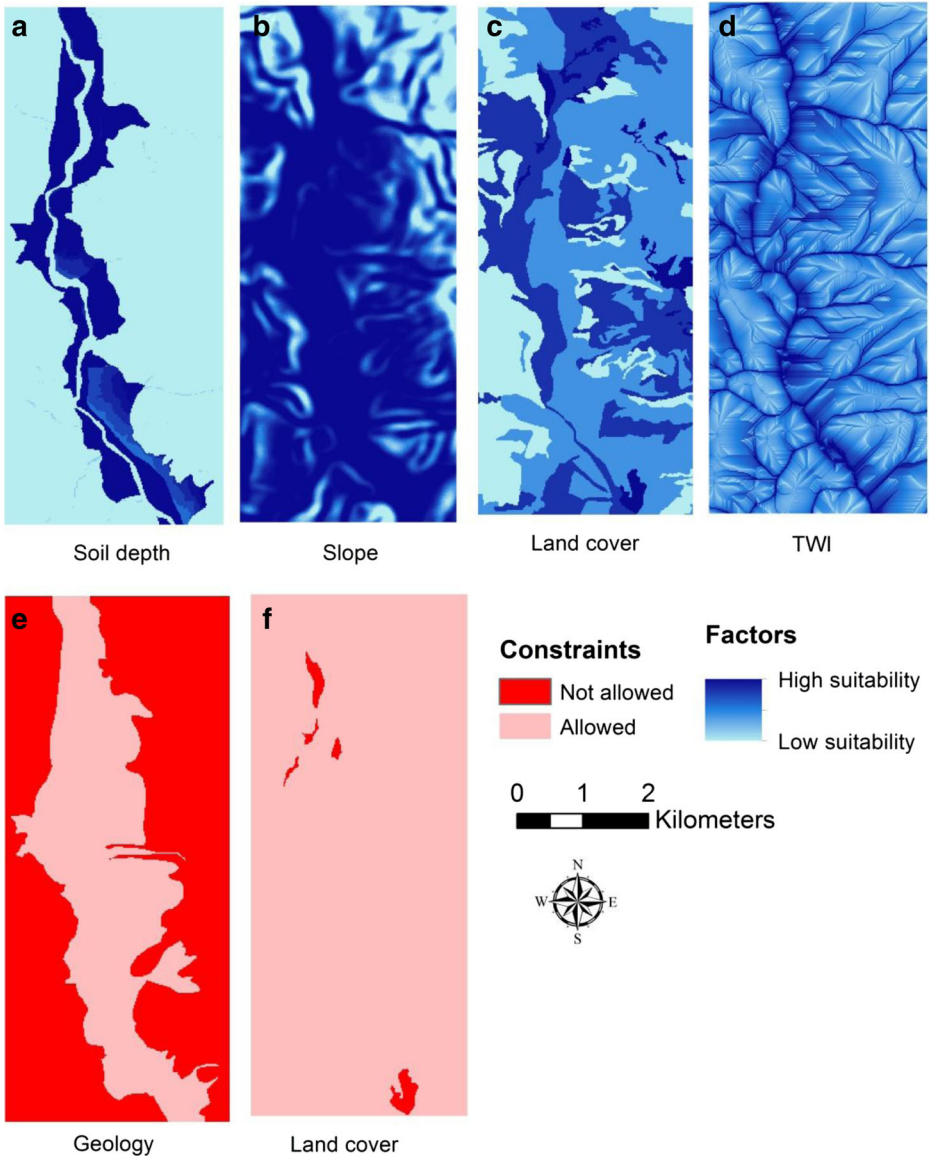


Fig. 6 Factors and constraints used to locate suitable sites for construction of subsurface dams, within the focus area in Fig. 1

Ishida et al. (2011) listed subsurface dams from several countries with the dam height ranging from 3 to 69 m, while the maximum modelled soil depth presented by Shafique et al. (2011a) for the current study area was 24 m. Here, a sigmoidal fuzzy membership function type with a symmetric shape was chosen for soil depth (Table 2 and Fig. 3a), where soil depths between 5 and 15 m were considered most suitable and were used as inflection points. Shallower aquifers below 5 m were excluded due to the smaller storage capacity. Deeper aquifers beyond 15 m were not considered as most suitable because of the inconvenience of

deep digging to reach bedrock. Subsurface dams should be placed in valleys with gentle slopes to be able to utilize maximum storage capacity behind the dam and to prevent rapid subsurface flows out of the system. Topographically, a gradient between 0.2 and 4 % has been considered adequate, but slopes up to 15 % have been used for construction of such dams (Nilsson 1988). A sigmoidal fuzzy membership function type with monotonically decreasing shape was considered for the slope factor with inflection points of 0 % and 15 % (Table 2 and Fig. 3b). Land cover was another factor where classes which allow more water infiltration were selected as most suitable with a sigmoidal fuzzy membership function type and a monotonically decreasing shape (Table 2 and Fig. 3c). Land cover classes were converted from categorical form to quantitative form through ranking of their suitability for locating subsurface dams, which enabled the use of these numbers as inflection points in a fuzzy membership function (Table 2).

In the AHP pairwise comparison, the weights, which were considered to be consistent, for soil depth, slope and TWI were 30 % for each (Table 3), while land cover was assigned the lowest weight of 10 %. In FIM, the calculated weights for soil depth, slope, land cover and TWI were 25 %, 41 %, 17 % and 17 %, respectively (Table 3).

Out of the total study area about 8 % (43 km²) was included in the suitability map; the rest was omitted due to constraints (Fig. 7). The suitability map derived from AHP yielded about 3 % (16 km²) of the total area as most suitable, 4 % (22 km²) as moderately suitable and 0.8 % (5 km²) as least suitable (Fig. 7a). The suitability map derived from FIM identified about 2.7 % (14 km²) of the total area as most suitable, about 4 % (22 km²) as moderately suitable and about 1 % (7 km²) as least suitable (Fig. 7b). About 87 % of the identified suitable sites were overlapping between the methods. The focus area in Fig. 7 (within the rectangle of Fig. 1) mainly covers the area of Gari Habib Ullah since the other populated areas such as Muzaffarabad and Balakot had very small areas that were considered most suitable (Figs. 1 and 7). Suitable sites for construction of subsurface dams were mainly concentrated in the central parts of the study area around the main river where the area had deeper permeable quaternary deposits at flatter terrains. In humid regions such as this study area, streams are typically gaining as they are fed by groundwater discharge. There are quite few tributaries that flow through the valleys and join the main river at several locations in this study area, around both the northern and southern populated areas (Fig. 7). These streams carry a fair amount of subsurface flow in wet seasons which could be stored in sediment layers by constructing subsurface dams. Such dams could be located just before the streams join the main river and could be used by neighbouring villages during dry seasons. Still, more detailed hydrological and hydrogeological field investigations would be needed for decision-making, before any actual execution of such dams.

Table 3 Pairwise comparison of the factors and weights calculated with the AHP method and weighting among the factors based on the FIM method

AHP						FIM		
	Criteria	Soil depth	Slope	Land cover	TWI	Weights (%)	Score Points	Weights (%)
Soil depth	1					30	15	25
Slope	1	1				30	25	41
Land cover	1/3	1/3	1			10	10	17
TWI	1	1	3	1		30	10	17

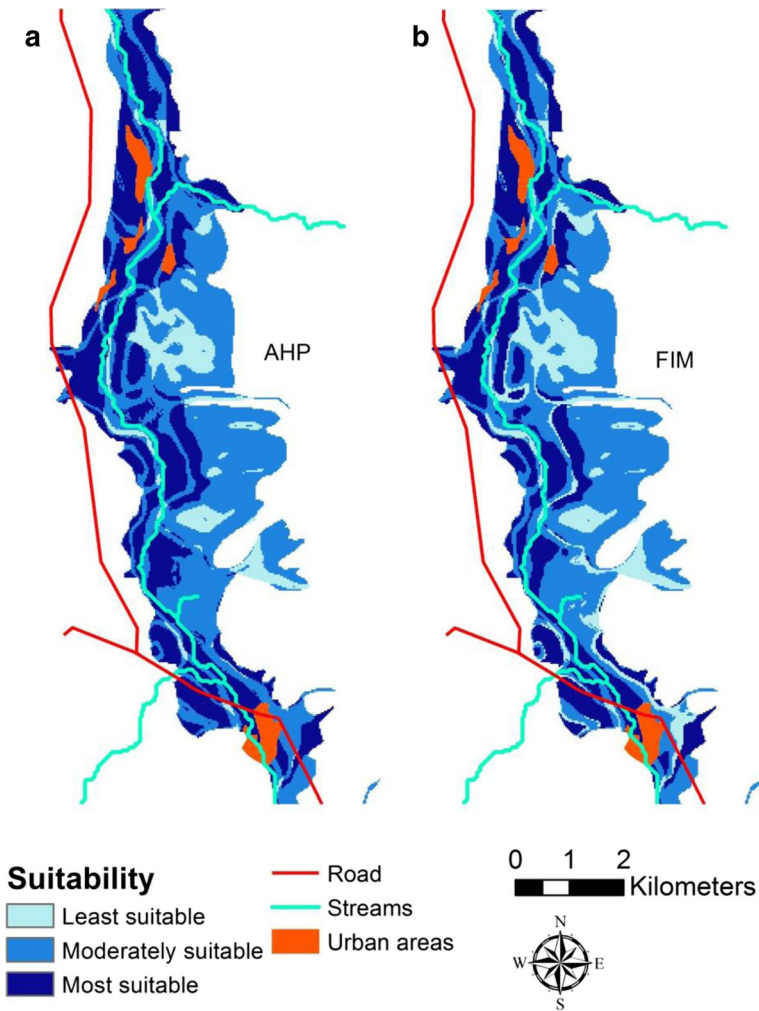


Fig. 7 View of the focus area (Fig. 1) showing the suitability for constructing subsurface dams derived with **a** the AHP and **b** the FIM weighting techniques

The sensitivity analysis suggested that the variation of 50 % in the weights of different factors caused a higher variation in the most suitable areas in the case of

Table 4 Sensitivity analysis by % variation in weights of the factors and % change in output in terms of the most suitable areas

50 % reduction in weights of the factors	Change in output in terms of the most suitable areas (%)	
	AHP	FIM
Soil depth	-14.6	-33
Slope	17	20
Land cover	-6.6	28.1
TWI	7	32

FIM compared to AHP (Table 4). Therefore, AHP was considered to be the more robust model for assigning weights in this study. Still, both AHP and FIM are dependent on scientific knowledge and expert judgment, and the state and relevance of these should be evaluated before using the results. In the current study, the steep terrain created strong contrasts to suitability within the area, which is why the physical factors could be seen as highly relevant for finding possibly suitable areas. Among individual factors, 50 % reduction in the weightage of soil depth reduced most suitable areas by 33 % in FIM and by 14.6 % in AHP. Furthermore, reduction in the weightage of TWI increased the most suitable areas by 32 % in FIM and by 7 % in the case of AHP. The AHP model was most sensitive to the slope and least sensitive to land cover and TWI (Table 4). The FIM method was most sensitive to soil depth and least sensitive to slope (Table 4).

The factor removal technique was performed for the full extent of the study area (Fig. 1). However, for visualization, results are only shown for the focus area (Fig. 8). The suitability map that was derived, when all factors were integrated with equal weights, yielded about 2 % (11 km²) of the whole study area as most suitable (see detail in Fig. 8a), where least suitable

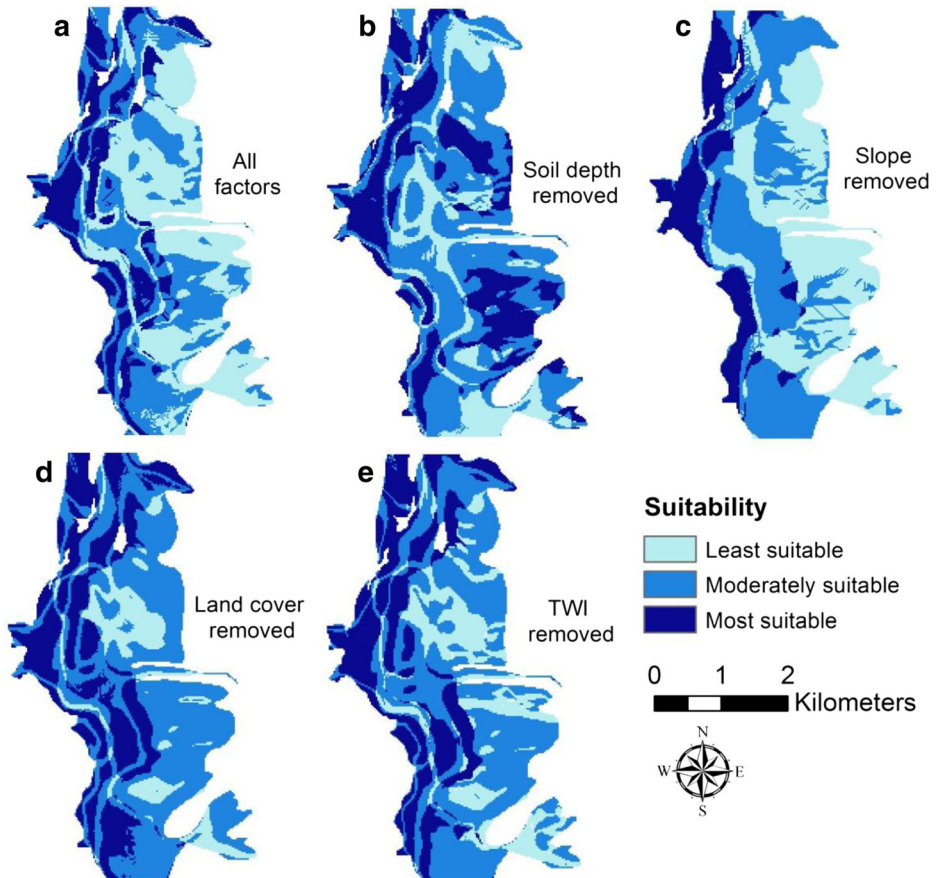


Fig. 8 Suitability maps demonstrating the factor removal technique, and corresponding local changes in the focus area, where the weights in **a**) were equally distributed to all factors and then one factor was removed at a time in **b**)–**e**)

areas were located mostly on the eastern side. The factor removal technique showed that the least sensitive factor was soil depth which on removal reduced the most suitable areas slightly, to 1.95 % of the study area (compared to 2% when all factors were integrated). The factor removal technique also showed that the most sensitive factor tended to be land cover which on removal increased the most suitable areas to 3 % of the study area, especially in the central and southern parts (see detail in Fig. 8d).

One of the suitability maps (AHP) combined with the TWI map was compared with a Google Earth map to illustrate and visually verify some most suitable sites for construction of subsurface dams (Fig. 9) (Google Earth 2010). The calculated TWI that represented the hydrological response of the study area was then compared with the visible streams. For demonstration purposes, two possible sites for construction of subsurface dams were identified in the vicinity of urban areas, where potentially suitable areas had high TWI values. A first potential site was located close to the Gari Habib Ullah city where a tributary flows into the Kunhar River (Fig. 9). Similarly the second potentially suitable site is located near the densely populated Muzaffarabad city where a tributary joins the Neelam River (Fig. 9).

The MCA framework enabled the integration of knowledge for decision making, where the weights had a more significant influence on the results than the choice of the weighting method, which is in line with Strager and Rosenberger (2006). One of the common criticisms on MCA is the subjective nature of the weighting procedure which is dependent on the judgement of experts, stakeholders and decision makers. However, participation of stakeholders may be more important in a later stage, while scientific knowledge and technical expertise often play the major role for the overall feasibility of such projects (Balasubramaniam et al. 2007). Yet, the weighting of

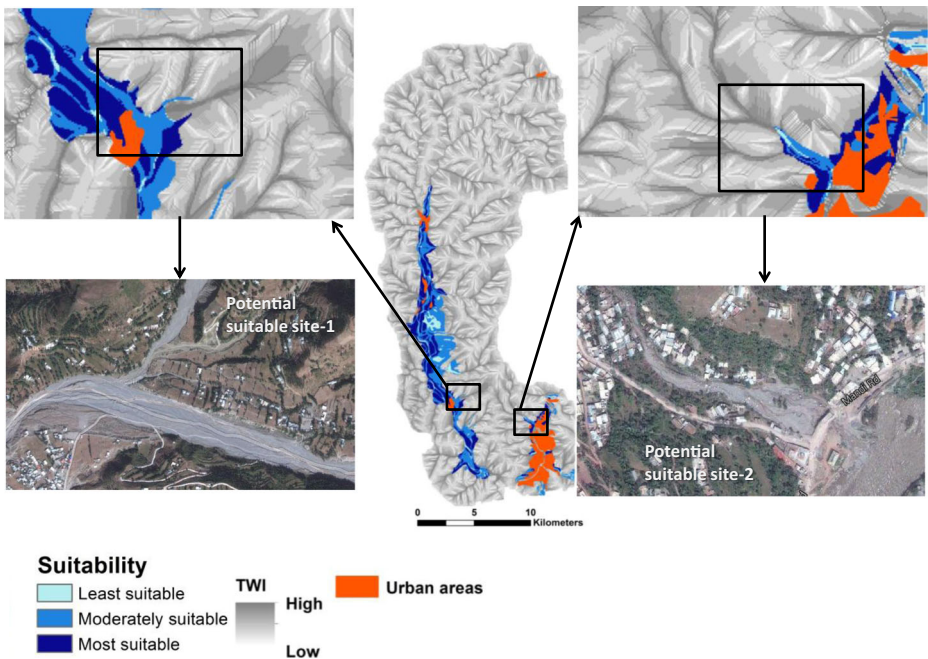


Fig. 9 Suitability map (AHP) with TWI data showing two potential sites for construction of subsurface dams which are compared with Google Earth maps (Google Earth 2010)

different influencing factors should be carefully designed and tested, while the most robust results could be seen as most promising for further investigations concerning the suitability for subsurface dams.

4 Conclusions

The paper presents a methodology to locate suitable sites for construction of subsurface dams using SMCA, integrating physical parameters such as geology, slope, land cover and soil depth in the northern parts of Pakistan. SMCA proved to be a useful tool in decision making where GIS plays a role in analysing spatial data and MCA provides procedures to structure decision problems. The evaluation of the weights for each factor is a crucial step in SMCA that often needs elicitation from expert judgements. Two weighting techniques, i.e. AHP and FIM, were employed and compared. The suitability map derived from AHP yielded about 3 % (16 km²) of the total area as most suitable, 4 % (22 km²) as moderately suitable and 0.8 % (5 km²) as least suitable. The suitability map derived from FIM identified about 2.7 % (14 km²) of the total area as most suitable, about 4 % (22 km²) as moderately suitable and about 1 % (7 km²) as least suitable. About 87 % of the identified suitable sites were overlapping between the methods. However, the sensitivity analysis suggested that AHP was a more robust weighting technique compared to FIM. The factor removal technique suggested that land cover, among the physical factors, was the most sensitive factor which on removal affected the most suitable areas to the highest extent. However, suitable areas identified with this methodology should be followed by more detailed hydrological and hydrogeological field investigations before any actual execution of such dams. The methodology presented here shows some promising results to be used as a part of early planning to locate suitable sites and to identify important physical factors for localization of subsurface dams.

Acknowledgments Lars Erik Lundbergs Scholarship Foundation (Dnr 2011/10, Dnr 2012/05, Dnr 2013/09, Dnr 2014/06) and Higher Education Commission (HEC) of Pakistan through Quaid-e-Awam University of Science and Technology, Nawabshah (QUEST/FDINP/EE&AF/10-751), Pakistan are acknowledged for funding this project. We are thankful to Caroline Karlsson, Emad Dehkordi, Xi Pang and Mårten Karlson for valuable inputs.

References

- Ahmad N (1982) An estimate of water loss by evaporation in Pakistan. Irrigation Drainage and Flood Control Research Council, Planning and Coordination Cell, Lahore
- Ahmad S, Hussain Z, Qureshi AS, Majeed R, Saleem M (2004) Drought Mitigation in Pakistan: Current Status and Options for Future Strategies. Working Paper 85, Drought Series. Paper: 3
- Al-Adamat R, Diabat A, Shatwani G (2010) Combining GIS with multicriteria decision making for siting water harvesting ponds in Northern Jordan. *J Arid Environ* 74:1471–1477
- Ali HM (2010) Fundamentals of irrigation and on-farm water management. Springer 1:556
- Anbazhagan A, Thingbaijam KKS, Nath SK, Narendara Kumar JN, Sitharam TG (2012) Multi-criteria seismic hazard evaluation for Bangalore city, India. *J Asian Earth Sci* 38:186–198
- Anwar OH (1983) The effect of a subsurface barrier on the conservation of freshwater in coastal aquifers. *Water Resour* 17(10):1257–1265
- ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) (2009) Retrieved in 2009 from <http://asterweb.jpl.nasa.gov>. ASTER GDEM is a product of METI and NASA
- Ayalew L, Yamagishi H (2005) The application of GIS-based logistic regression for landslide susceptibility mapping in the Kakuda-Yahiko Mountains, Central Japan. *Geomorphology* 65:15–31

- Babiker IS, Mohamed MAA, Hiyama T, Kato K (2005) A GIS-based DRASTIC model for assessing aquifer vulnerability in Kakamigahara Heights, Gifu Prefecture, central Japan. *Sci Total Environ* 345:127–140
- Balasubramaniam A, Boyle AR, Voulvoulis N (2007) Improving petroleum contaminated land remediation decision-making through the MCA weighting process. *Chemosphere* 66:791–798
- Basharat M, Rohn J, Baig MS, Ehret D (2012) The lithological and structural control of Hattian Bala rock avalanche triggered by the Kashmir earthquake 2005, Sub-Himalayas, Northern Pakistan. *J Earth Sci* 23(2):213–224
- Baume G (1984) Trap-dams: artificial subsurface storage of water. *Water Int* 9:2–9
- Bazilian M, Rogner H, Howells M, Hermann S, Arent D, Gielen D, Steduto P, Mueller A, Komor P, Tol RSJ, Yumkella KK (2011) Considering the energy, water and food nexus: towards an integrated modelling approach. *Energy Policy* 39:7896–7906
- Beven K, Kirkby M (1979) A physically based variable contributing area model of basin hydrology. *Hydrol Sci Bull* 24(1):43–69
- Bhatti SS, Khattak KNM, Roohi R (2008) Planning water resources and management in Pishin-lora river basin of Baluchistan using GIS/RS. Second International Conference on Advances in Space Technologies Islamabad, Pakistan 29th -30th November
- Chenini I, Mammou AB, May ME (2010) Groundwater recharge zone mapping using GIS-based multi-criteria analysis: a case study in Central Tunisia (Maknassy Basin). *Water Resour Manag* 24:921–939
- DCR (1998) District Census Report (1998) Population Census Organization, Government of Pakistan, Islamabad, Pakistan
- Dhakate R, Rao G, Raju A, Mahesh J, Rao J, Sankaran S (2013) Integrated approach for identifying suitable sites for rainwater harvesting structures for groundwater augmentation in Basaltic Terrain. *Water Resour Manag* 27:1279–1299
- Eastman JR (1999) Multi-criteria evaluation and GIS. In: Longley PA, Goodchild MF, Maguire DJ, Rhind DW (eds) *Geographical information systems*. John Wiley and Sons, New York, pp 493–502
- Eastman JR (2006) *IDRISI Andes-Guide to GIS and image processing*. Clark labs, Clark University
- ESRI (Environmental Systems Research Institute) (2013) *ArcGIS Resource Center Desktop 10 – How Subset Features works*. Retrieved January 9 2014 from: <http://help.arcgis.com/en/arcgisdesktop/10.0/help/index.html#/0031000009m000000>
- Fernández DS, Lutz MA (2010) Urban flood hazard zoning in Tucumán Province, Argentina, using GIS and multicriteria decision analysis. *Eng Geol* 111:90–98
- Google Earth 6.0 (2010) Muzaffarabad 34°21'34.87"N, 73°28'15.79"E, elevation 2226M. <<http://www.google.com/earth/index.html>> [Viewed April 07, 2014]
- Graymore MLM, Wallis AM, Richards AJ (2009) An Index of Regional Sustainability: a GIS-based multiple criteria analysis decision support system for progressing sustainability. *Ecol Complex* 6:453–462
- GSP (Geological Survey of Pakistan) (2009) Retrieved in 2009 from <http://www.gsp.gov.pk/>
- Haq I, Abbas TS (2006) Sedimentation of Tarbela and Mangla reservoirs. Pakistan Engineering Congress, 70th annual session proceedings. Paper No. 659
- Hendrickx JMH, Khan AS, Bannink MH, Birch D, Kidd C (1991) Numerical analysis of groundwater recharge through stony soils using limited data. *J Hydrol* 127(1–4):173–192
- Hussain A, Mughal N, Haq I, Latif A (2004) Geological map of the Gari Habib Ullah area, district Manshehra and parts of Muzaffarabad district. AJK, Geological Map Series. Geological Survey of Pakistan, Islamabad-Pakistan
- Ibrahim MB (2009) Rainwater Harvesting for Urban Areas: a Success Story from Gadarif City in Central Sudan. *Water Resour Manag* 23:2727–2736
- Ishida S, Tsuchihara T, Imaizumi M (2006) Fluctuation of NO₃-N in groundwater of the reservoir of the Sunagawa subsurface dam, Miyako Island, Japan. *Paddy Water Environ* 4:101–110
- Ishida S, Tsuchihara T, Yoshimoto S, Imaizumi M (2011) Sustainable use of groundwater with underground dams. *JARQ* 45(1):51–61
- Jamali AI, Olofsson B, Mörtberg U (2013) Locating suitable sites for construction of subsurface dams using GIS. *Environ Earth Sci* 70:2511–2525
- Jha MK, Chowdary VM, Kulkarni Y, Mal BC (2014) Rainwater harvesting planning using geospatial techniques and multicriteria decision analysis. *Resour Conserv Recycl* 83:96–111
- Kamp U, Growley BJ, Khattak GA, Owen LA (2008) GIS-based landslide susceptibility mapping for the 2005 Kashmir earthquake region. *Geomorphology* 101:631–642
- Kessides IN (2013) Chaos in power: Pakistan's electricity crisis. *Energy Policy* 55:271–285
- Kourgiyalas NN, Karatzas GP (2011) Flood management and a GIS modelling method to assess flood-hazard areas-a case study. *Hydrol Sci J* 56(2):212–225
- Latif A, Afridi AGK, Majid AN (2008) Geological map of the Balakot quadrangle (Earthquake affected area), District Manshehra, NWFP, Pakistan, Geological Map Series. Geological Survey of Pakistan, Islamabad-Pakistan

- Lodwick WA, Monson W, Svoboda L (1990) Attribute error and sensitivity analysis of map operations in geographical information systems: suitability analysis. *Int J Geogr Inf Syst* 4(4):413–428
- Machiwal D, Jha MK, Mal MC (2011) Assessment of groundwater potential in a Semi-Arid Region of India using remote sensing, GIS and MCDM techniques. *Water Resour Manag* 25:1359–1386
- Malczewski J (1999) GIS and multicriteria decision analysis. John Wiley and Sons, New York
- Malczewski J (2000) Review article on the use of weighted linear combination method in GIS: common and bestpractice approaches. *Trans GIS* 4(1):5–22
- Malczewski J (2004) GIS-based land-use suitability analysis: a critical overview. *Prog Plan* 62:3–65
- Ministry of the environment Japan (2004) Model project to combat desertification in Nare village, Bukina Faso. Technical report of the subsurface dam. Available at: <http://www.env.go.jp/earth/report/h16-08/eng/index.html>
- Mirza UK, Ahmad N, Majeed T, Harijan K (2008) Hydropower use in Pakistan: past, present and future. *Renew Sustain Energy Rev* 12:1641–1651
- Mukherjee P, Singh CK, Mukherjee S (2012) Delineation of groundwater potential zones in arid region of India-A remote sensing and GIS approach. *Water Resour Manag* 26:2643–2672
- Nilsson A (1988) Groundwater dams for small-scale water supply. Intermediate Technology Publications Limited, London: 69
- Pakistan Bureau of Statistics (2012) Accessed from <http://www.statpak.gov.pk> on January 12, 2012
- Pakistan Meteorological Department (2011) Accessed from <http://www.pakmet.com.pk> on January 13, 2012
- Quinn PF, Beven KJ, Lamb R (1995) The $\ln(a/\tan\beta)$ index: how to calculate it and how to use it within the TOPMODEL framework. *Hydrol Process* 9(2):161–182
- Qureshi ME, Harrison SR, Wegener MK (1999) Validation of multi-criteria analysis models. *Agric Syst* 62:105–116
- Qureshi SA, McCinick GP, Sarwar A, Sharma A (2010) Challenges and prospects of sustainable groundwater management in the Indus Basin, Pakistan. *Water Resour Manag* 24:1551–1569
- Rahman MA, Rusteberg B, Gogu RC, Ferreira JPL, Sauter M (2012) A new spatial multi-criteria decision support tool for site selection for implementation of managed aquifer recharge. *J Environ Manag* 99:61–75
- Rahman MA, Rusteberg B, Uddin MS, Lutz A, Saada MA, Sauter M (2013) An integrated study of spatial multicriteria analysis and mathematical modelling for managed aquifer recharge site suitability mapping and site ranking at Northern Gaza coastal aquifer. *J Environ Manag* 124:25–39
- Raju JN, Reddy VKT, Munirathnam P (2006) Subsurface dams to harvest rain water-A case study of the swarnamukhi river basin, Southern India. *Hydrogeol J* 14:526–531
- Saaty TL (1980) The analytic hierarchy process. Mc Graw Hill Company, New York
- Scally FAD (1994) Relative importance of snow accumulation and monsoon rainfall data for estimating annual runoff, Jhelum basin, Pakistan. *Hydrol Sci* 39:199–216
- Shaban A, Khawlie M, Bou Kheir R, Abdullah C (2001) Assessment of road instability along a typical mountainous road using GIS and aerial photos, Lebanon-eastern Mediterranean. *Bull Eng Geol Environ* 60:93–101
- Shafique M, van der Meijde M, Rossiter GD (2011a) Geophysical and remote sensing-based approach to model regolith thickness in a data-sparse environment. *Catena* 87:11–19
- Shafique M, van der Meijde M, Ullah S (2011b) Regolith modeling and its relation to earthquake induced building damage: a remote sensing approach. *J Asian Earth Sci* 42(1–2):65–75
- Shiklomanov A (1999) Scientific Leader and Editor State Hydrological Institute (SHI) St. Petersburg
- Strager MP, Rosenberger R (2006) Incorporating stakeholder preferences for land conservation: weights and measures in spatial MCA. *Ecol Econ* 58(1):79–92
- Sugio S, Nakada K, Urish DW (1987) Subsurface seawater intrusion barriers analysis. *J Hydraul Eng* 113:767–779
- Suleman S, Wood MK, Shah BH, Murray M (1995) Development of a rainwater harvesting system for increasing soil moisture in arid rangelands of Pakistan. *J Arid Environ* 31(4):471–481
- Tariq MAUR, Van de Giesen N (2012) Floods and flood management in Pakistan. *Phys Chem Earth* 47–48:11–20
- UN-Water Work Programme (2010) Accessed online from http://www.unwater.org/downloads/UNW_Workplan_2010_2011.pdf on April 02, 2012
- USAID (2009) Pakistan's food and agriculture system. Nathan Associates Inc