

Managing flood water of hill torrents as potential source for irrigation

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Abstract

This paper presents an integrated methodology for sustainable development planning to conserve the excess water resources. This developed methodology takes advantage of geographic information systems software to integrate its strength to manage the flood impacts. This approach is of dual purpose: first, to reduce the flash flood hazard of hill torrents; and second, to make use of flood water as a source of irrigation by conserving flood water in an earthen reservoir. The developed integrated methodology works as a decision-making system for selection of best site selection for earthen reservoir. The results for three potential sites for earthen reservoir supports in a decision-making process for best site for reservoir by analysing calculations for storage capacity, earthen works, and lengths of canals from reservoirs to agricultural land. This study investigated that the tools of geoinformatics have the potential to resolve the engineering challenges linked with mitigation of flood hazards. It is evident from the study that practical considerations for future turn the study into an informational tool to mitigate flood.

Introduction

Efficient management of flash floods for its application for agricultural purposes can be achieved through sustainable water management planning. Advantages of flood water harvesting would be considered as twofolds, i.e. to save the flood losses and to provide the storage facility for reservoirs. Enhanced agricultural productivity could be ensured through the use of sustainable irrigation systems (Deng *et al.*, 2006), and a wise development planning for well-managed hydro-infrastructure at national level would contribute towards food security. Similarly, at local level, best practices would be introduced and implemented through networking of all stakeholders (Madramootoo *et al.*, 2009). A terminology 'spate irrigation' is used for flood water harvesting, and this kind of irrigation is under practice in hill torrent areas of Pakistan for agricultural production for the last several hundred years during the season of monsoon and the study area falls under low rainfall zone. A previous study has shown that harvesting floods of hill torrents would contribute for crops production, and this strategy is needed for the livelihoods of community with food security.

There are 13 major hill torrents (Anon, 2007), originated from Suleiman Range and flow through Dera Ghazi Khan

(D.G. Khan) towards the River Indus. During monsoon season, when flash flood events are occurring in the hill torrents catchments, the flood water is diverted to the fields (Ako *et al.*, 2010) for crop sowing or to store the moisture. There is major problem due to the use of earthen bund in this kind of practice. The overtopping of the bunds leads to uncontrolled flooding, while the bunds are often washed away causing severe problems of heavy depositions of sediment (Tesfai and Stroosnijder, 2001). This sedimentation, on the other hand, has positive aspect as nutrients addition for soil (Pavanelli and Cavazza, 2010). Hence, potential prospect of controlled flash floods would be development to meet growing demands of water for agriculture. Considering this opportunity, during 2005, a development project to manage the hill torrents of D.G. Khan was approved by the Government of Punjab. Water resources development and management is imperative for sustainable agriculture in water scarce areas.

The flood management through developing cost-effective flood diversion structures have been intensively investigated (World Meteorological Organization, 2012). On contrary, in several studies, it is described that improving system efficiency through modernisation of the diversion and distribution structures is not feasible because of heavy

sedimentation in flood carrying channels (Komakech *et al.*, 2011). Other modernised suggestion include to avoid extension of command area and field bund heights of more than 1 m and to adopt the process of field water distribution from one field to next downstream filed rather than individual field water distribution (Mehari *et al.*, 2011). However, in context of hill torrents management through tools of hydro-informatics, there is a little information. Such information is essential for most effective development planning. Therefore, in this study, integrated methodology was developed for flood-related data processing through software applications of ArcGIS (ESRI, Redlands, CA, USA) and Global Mapper (Blue marble Geographics, Hallowell, Maine, USA). These tools allowed (i) minimising possible errors due to the usage of conventional flood mapping (Lee *et al.*, 1992) and (ii) rapid site feasibility for earthen reservoirs, which normally required an efficient management of detailed data. These data include river networks characteristics, soil characteristics, rain fall and run-off data.

The developed integrated methodology required an important preliminary step, i.e. production of digital elevation model (DEM) for flood inundation mapping using topographical data. In order to make the best use of outputs, mutual research cooperation was established with related institutions, i.e. Water Resources Research Institute (WRRI), Pakistan, and Water Resources Section of Planning Commission of Pakistan.

The practical applications of study are discussed in this paper. The methodology was applied to develop integrated hydro-informatics tools for identification of location for earthen reservoir for flood management of Vehowa hill torrents, situated in a district of D.G. Khan, Pakistan. When we compare used methodology with other available approaches then, it was found that in hydraulic engineering, alternatively, we can use numerical modelling. While using such approach, these tools require taking into account a large number of datasets and coupling appropriate computational codes. Moreover, there is possibility for lack of information in an existing model. Therefore, in this study, geoinformatics tools are used to handle with the issues of complex coding and insufficient datasets (Malleron *et al.*, 2011).

Material and methods

Study area

Under this study, hill torrents of D.G. Khan district were selected. This study area consists of two parts: (i) area irrigated under spate irrigation system and (ii) area irrigated through canal system. The east side across the canal is irrigated through canal intake, and west side across the canal is irrigated through spate irrigation. After identification of the study area, it was required to prepare a detailed map to

integrate it with geodatabase using ArcGIS software application. The purpose of generating this geodatabase (databank with multiple layers of maps, satellite images, global positioning system (GPS) survey, etc.) was to provide a digital data source for further future research and development of hill torrents in the area. This was the practical application of adopted approach. Nowadays, application of GIS in the water sector is widespread (Sanyal and Lu, 2004), including applications to watershed management, flood management and water quality. On the other hand, organisation and management of geodatabase is very important for the establishment of water conservation.

Integrated methodology

The procedural approach, to establish an integrated methodology and to build a roadmap to achieve the study objectives, is illustrated in Figure 1 followed by stepwise explanation.

Data processing

Hydro-informatics approach consists of developing a set of tools to collect and process data in a consistent manner (Heaney *et al.*, 2000), and digital mapping is one of the tools facilitating the decision makers and analysts to achieve their objectives with ease. The salient digitised features on satellite

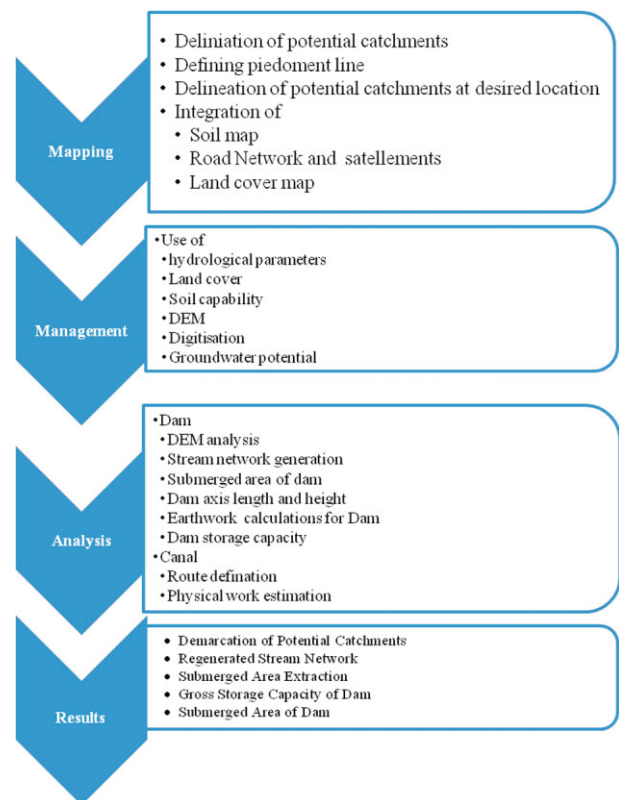


Figure 1 Result-oriented integrated methodology.

image [SPOT, Resolution 2.5 m, 2007; Centre National d'Etudes Spatiales (CNES), Toulouse, France] and topographic sheet were prepared. These features included the layers of road network, stream network and catchment area. All these features including irrigation network, field boundaries, road network, population area and agricultural area were embedded as a layer of geodatabase. Data layers integration in GIS is a desirable feature (Gómez *et al.*, 2009), and for this reason, integration of information layers (satellite images, digitised maps, contours, stream network, fields, etc.) through different operations like georeferencing, overlaying and clipping was performed to prepare integrated but spatially consistent data layers.

Defining piedmont line and land use classification

Identification of piedmont (hill foot) line at the foot of Suleiman mountain range was required to decide over and selection of the drainage points and their relevant catchments for the study area. To define the piedmont line, the maps of the study area, DEM and satellite image were used to draw a line separating the hill foot and plain land area. The purpose of this line was to define the drainage points along this line. After defining the route of piedmont line, the districts map was overlaid to check the route passage through administrative boundaries. Similarly, land use map was produced, and it was clear from the map that the major portion of the catchment areas was mountainous and covered with small patches of vegetation and settlements. The adopted methodology for the supervised image classification for land use map was carried out using Erdas Imagine software application (ERDAS, Inc., Hexagon Group, Sweden) (Shahapure *et al.*, 2010).

Delineation of potential catchments

Identification of potential catchments, contributing for flood water in hill torrents, was a desired action for its inclusion in a development plan. The delineation of these catchments areas with corresponding drainage points and stream network was carried out using digitised topographical sheets of the area (Czekanski and McKinney, 2006). The catchments and stream network was then integrated with administrative boundaries.

Water potential to be managed

The hydrological parameters are essential prior to the site selection and preparation of development plan. The data for annual run-off volume for floods were obtained from a report of National Engineering Services Pakistan. There are 37 stations for hydrology data collection in entire catchment of D.G. Khan hill torrents, where precipitation records are observed regularly. These stations are operated by Irrigation

& Power Department of the Government of Punjab, Water and Power Development Authority and Pakistan Meteorological Department. Hydrological phenomenon generally results because of highly complex natural events, and structural measures for flood water management requires the knowledge of the probability of occurrence and the risk coverage for appropriate designing. Flood frequency and peak discharge estimates (NESPAC, 1998) for Vehowa hill torrent of D.G. Khan is listed in Table 1.

Digitisation for command area

Detailed digitisation for linear and area features on SPOT satellite image (2.5 m resolution, 2007) of the command area was carried out. In this digitisation process, main layers were agricultural fields, settlements, streams, river, alluvial fan, roads and outlining of command area boundary. The outlining of command area boundary was marked through image interpretation and drainage pattern study by consulting GIS specialist and field experienced staff of WRRRI of National Agriculture Research Centre, Pakistan.

Groundwater potential within catchment area

Hydro-geological map of relevant area was clipped and digitised, and areas having groundwater potential were identified as a separate vector layer as shown in Figure 2.

DEM analysis

Records of elevation values were found by importing DEM in Surfer software application. The graphical presentation of

Table 1 Flood frequency and peak discharge estimation in Vehowa catchment

Return period	2.33 year (m ³ /s)	5 year (m ³ /s)	10 year (m ³ /s)	25 year (m ³ /s)
Flood frequency	1038	1556	1979	2512
Peak discharge	1123	1684	2140	2718

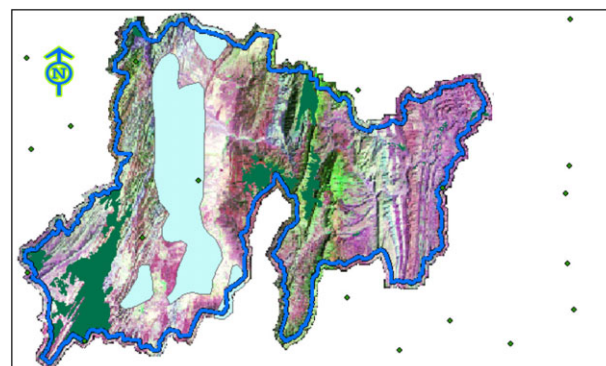


Figure 2 Overlay of groundwater potential areas over image of catchment.

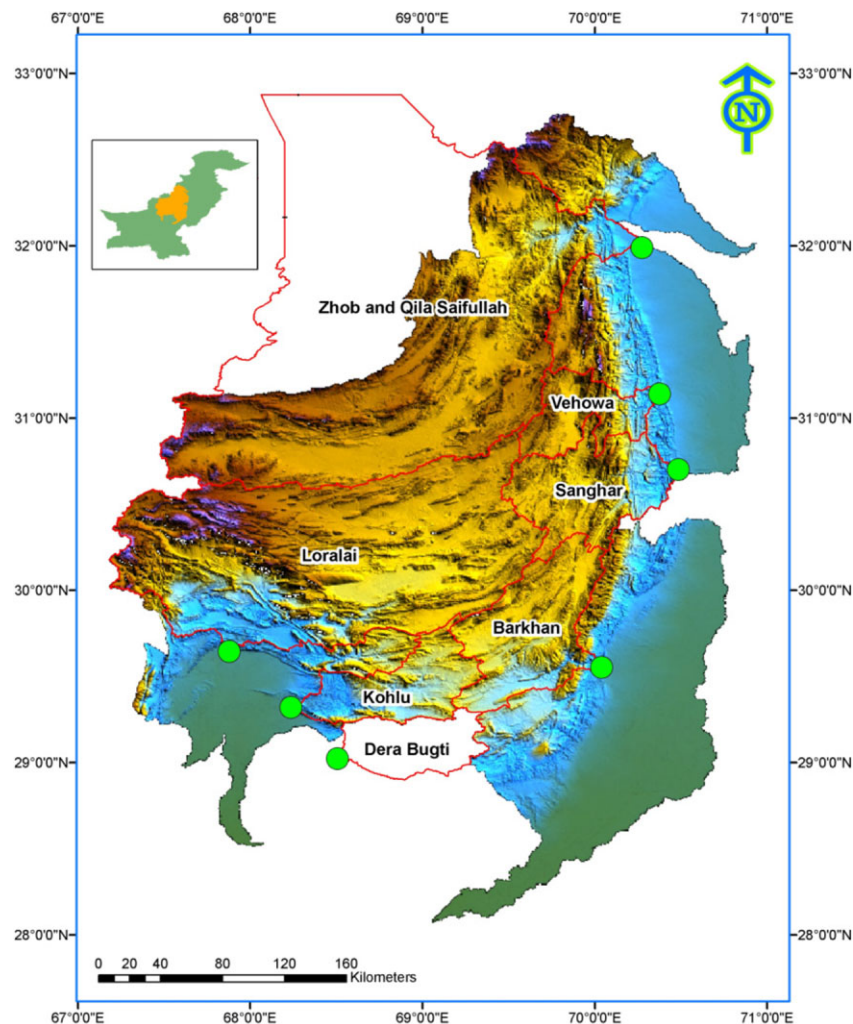


Figure 3 Identified potential catchments and nomenclature.

the Z values (elevations) for Vehowa basin made it easy in finding accurate positions for drainage points of catchments. These Z values ranging from 1930 m to 2098 m helped to make it understand about the hilly terrain of the study area.

Results and discussion

Demarcation of potential catchments

Demarcation of potential catchments and nomenclature was produced at respective drainage points along the piedmont line using Arc Hydro tools of Arc GIS. The naming of catchments was based on the district name having a major portion of catchments as given in Figure 3. Calculated areas of these potential catchments are provided in Table 2. The necessary step for management of flood water system is to identify potential catchments (Todini, 1999) because these catchments sometimes would act as natural flood barrier. However, these demarcated catchments were found having

Table 2 Calculated areas for potential catchments

Demarcated catchment	Area (km ²)
Zhob-qila saifullah	38 321
Loralai	21 530
Barkhan	5 488
Sanghar	4 794
Kohlu	3 509
Dera bughti	2 649
Vehowa	2 596

no such natural feature for the control of flash floods. This situation further guided to take consideration for structural measurement for flood management. This kind of measure is adopted in most situations (McMinn *et al.*, 2010), but this is not necessary, as it depends on many other factors like cost and priority for a specific sector. Therefore, non-structural measure is adopted (Chang, 2008) and sometimes both would be applied (Steinführer *et al.*, 2009).

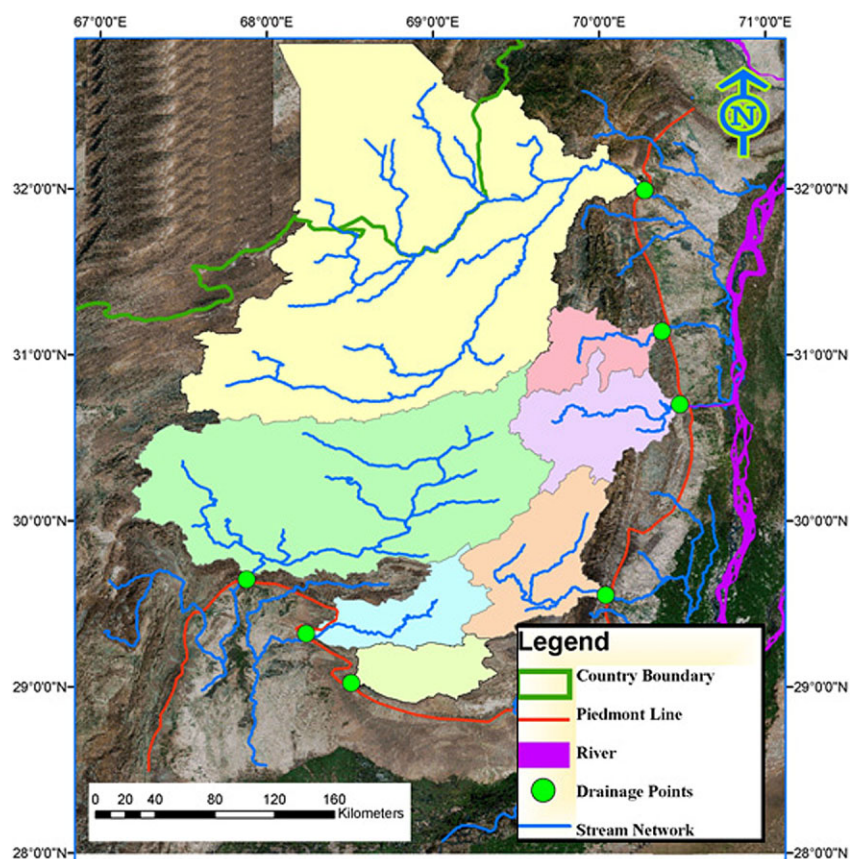


Figure 4 Trans-boundary water of Pakistan and Afghanistan.

Trans-boundary water

Zhob-Qilla Saifullah catchment was only among delineated catchments, which was spread over Pakistan and Afghanistan, as depicted in Figure 4. The trans-boundary contribution of water from Afghanistan to Pakistan helped to consider this part of water management through international rules of trans-boundary water. The majority of the world's population living in river basins that are internationally shared (trans-boundary basins) becomes important to take into consideration the international obligations in trans-boundary water resources management (Jarraud, 2009).

Land use classification in Vehowa command area

Previous studies have shown that land use change affect the hydrology that determines flood hazard and transportation of pollutants (Bronstert *et al.*, 2002). The land use map was georeferenced and digitised for the Vehowa command area, and results are provided in Table 3. Conversely this classification may be produced using Geo interpretation model for land use classification. In this study, model-based classification was not preferred because of the availability of land use map for the study area.

Table 3 Areas and perimeter values for land capability classes

Layer	Perimeter (km)	Area (km ²)
Good irrigated	28	27
Unproductive	24	30
Poor grazing	22	13
Torrent watered	67	104
Moderate irrigable	26	12

Stream network and length calculations

Stream networks for Vehowa catchment and command areas were generated using watershed tools in Arc GIS. In catchment areas, stream network was generated using topographic information whereas streams in command areas were digitised using satellite image. Corresponding lengths of streams were calculated using geometry tool in ArcGIS. DEM resolution would affect positional accuracy of derived hydrologic networks (Mcmaister, 2002); this finding was applied to avoid error in positional accuracy of stream network with a process cross-matching of derived network with digitised network.

Design Parameters	Site-I	Site-II	Site-III
Dam Location (Lat, Long)	31°07'27.19"N, 70°04'01.62"E	31°05' 42.86"N, 70°01'48.51"E	31°06'22.43"N, 70°09'46.98"E
Dam Height from datum line	1270 m	1192 m	914 m
Dam Axis Length	1340 m	1210 m	1188 m
Submerged Area (Hectors)	972.866	390.927	383.643

Figure 5 Sites comparison and analysis for selection of best option.

Sites comparison and analysis

After selecting the dam, axis location and direction over the DEM different values of dam heights were assigned. Each value of dam heights resulted in different extents of submerged area. The suitable heights for all three dam sites were selected by considering groundwater potential, land cover,

soil type and settlements. The calculated dam selection parameters are described in Figure 5, and comparative analysis is depicted in Table 4. It can be concluded that site-I is comparatively more feasible by considering four design parameters: (i) dam height from the datum line, (ii) dam axis length, (iii) submerged area and (iv) gross storage capacity of the dams.

Table 4 Different dam site options and analytical design comparison

Design Parameters	Site-I	Site-II	Site-III
Dam location	31°07'27.19"N, 70°04'01.62"E	31°05'42.86"N, 70°01'48.51"E	31°06'22.43"N, 70°09'46.98"E
Dam height (m)	1270	1192	914
Dam axis length (m)	1340	1210	1188
Submerged area (ha)	972	390	383
Gross storage (MCM)	1730	775	689

Table 5 Cut and filled soil works for proposed earthen reservoir

Parameter	Results
Cut volume	65 m ³
Cut surface	52 m ²
Fill volume	284 325 m ³
Fill surface area	2 045 m ²

On the basis of above analysis, an earthen reservoir was proposed at upstream of Vehowa command area to store flash flood water for assured water supply according to water demand. There are another approaches called two-dimensional nonlinear and three-dimensional (3D) nonlinear dynamic finite element analyses of an earth dam considering the earthquake effects (Prevost *et al.*, 1985). As proposed, earthen reservoir is based on low cost; because of this reason, this factor of comparison was not adhered. However, feasibility study of this earthen reservoir was needed to plan economically viable project to control hill torrent floods for conservation. This feasibility study included calculation for physical works like cut and fill volumes of soil. This estimation for cut and filled works was produced using Global Mapper software application. Results, as given in Table 5, would be considered appropriate because of reason that farmers can handle this amount of physical works through their own resources.

For proposed site, a comparative analysis of reservoir height from datum to its water storage capacity was performed, and results are provided in Table 6.

Proposed canal from earthen reservoir to command area

Water from earthen reservoir was proposed to draw through the least distant canal. The design of the canal (shape, width, side slopes, freeboard) depends on the design capacity of the canal (June, 2010), which is calculated by considering maximum crop water requirement. However, during this study, only least distance parameter was considered. But used software application Global Mapper was able to calculate the construction work calculations. To test this capability, a test width of 2 m for canal was selected, and accordingly, results were generated. A Longitudinal cross-sectional profile is

Table 6 Storage capacity analysis as a function of reservoir height

Sr. #	Dam height (m)	Storage capacity (MCM)
1	1270	1730
2	1269	1680
3	1268	1630
4	1267	1590
5	1266	1540
6	1265	1500
7	1264	1450
8	1263	1400
9	1262	1360
10	1261	1310
11	1260	1260

shown in Figure 6, along least distant path while estimated construction work calculations are provided in Table 7.

Preparation of 3D models for hydraulic structures

Using AutoCAD (Autodesk, Inc., San Rafael, CA, USA), 3D models for canal cross section, field watercourse cross section, canal outlets and field inlets were prepared. These models were generated to assist farmers so that they would carry out work at their own with ease of understanding. These structures were suggested to manage the flood water at field level.

Hydro-informatics geodatabase

The geodatabase format has advantage to increase the integration process between ArcGIS and spread sheets (Maran, 2010). Moreover, remote sensing data would be updated at any stage of project, and these data have a lead to monitored the flood events very well (Gläßer and Reinartz, 2005). At the end of this research, database was consisted of different data sets of satellite images, topographical sheets, land cover, catchment areas, networks of streams and drainage points as integrated geodatabase using ArcGIS. This was the basic source of technical information, which was used for preparation of results, and hence, it is recommended to retrieve information as a base data for further research.

Conclusions

The beneficiaries of managed flood water would have conflict. This situation is particularly evident among upstream

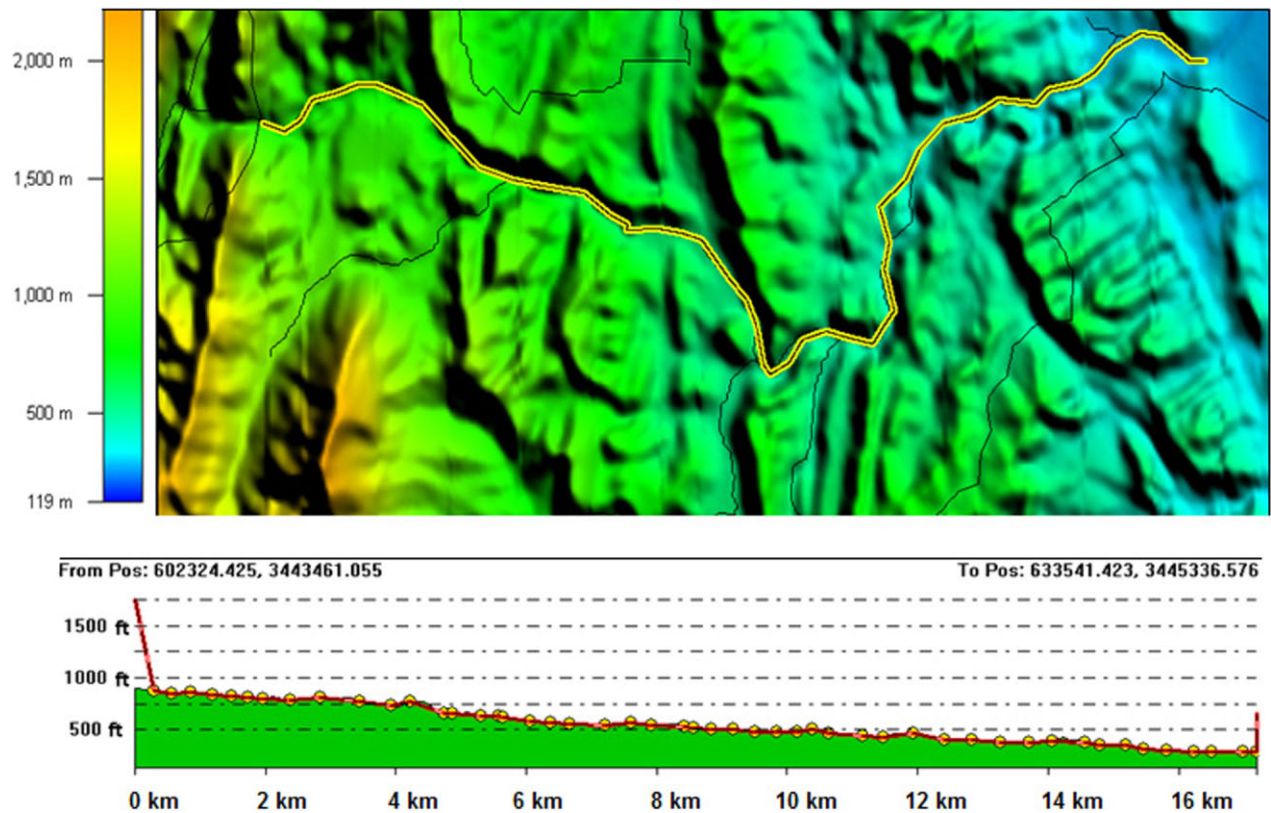


Figure 6 Longitudinal cross-sectional profile of canal.

Table 7 Construction work estimation for proposed canal

Parameter	Description
Cut volume	65 118 m ³
Cut surface area	7 790 m ²
Fill volume	152 208 m ³
Fill surface area	7 920 m ²
Total length	16 km
Width of proposed canal	2 m

and downstream water users, mainly due to increase in demand for a diminishing resource (Mul *et al.*, 2011). The solution to this situation is that once the development plan starts its operation, flood water sharing arrangements among farmers can be established at subcatchment scale, including earthen reservoirs, watercourses and well-managed agricultural fields (Mehari *et al.*, 2008). Even though being based on technical and engineering parameters, the sustainable development requires coordination of the decision-making bodies (in this case, farmers), and this objective would be achieved through mutual consultative process (Papa and Gleason, 2012).

GIS is a sophisticated technology because of its capabilities for presenting results. These results, originally in digital format, were embedded in the geodatabase as individual

layers of data. It was observed during the study that embedding the results in a geodatabase data as layer format makes them easily modifiable, editable and accessible for reuse, a functionality that is frequently required for development of sustainable systems and preparation of projects. Moreover, access to critical data, which is most useful during flood disaster management, turn this system into an informational tool that can be used by concerned authorities during pre and post decision making. Thus, results have demonstrated that dual purpose of reducing flood hazard and harvesting flood water for irrigation supply would prove as a pilot study for other similar areas as well as at river basin level. The rapid process of site feasibility for earthen reservoir is a salient feature of this study. However, reservoir model would be developed for reservoir storage calculations for future research. It creates one more research field, as a way forward from better to best approach. This modelling approach has further scope for future research works to manage flash floods of hill torrents.

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