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Harnessing Floodwater of Hill Torrents for Improved Spate Irrigation System Using Geo-Informatics Approach

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Abstract

In semi-arid regions, sustainability of agricultural system is most demanding in view of economical approaches for agricultural water management and its ensured availability. Flood flows of hill torrents have potential prospects for development to meet growing demands of water for agriculture. However to harvest this potential through traditional systems is not a success story. This paper discusses GIS and Remote Sensing tools application as a strategy to explore viable and economical prospective of floodwater management for spate irrigation. The fundamental problem is the optimal conservation of hill torrents flows and management of these water resources. To tackle this problem, a study for reservoir site selection was carried out. In this study, we present cost effective approach to mitigate the flood hazard while conserving this floodwater as irrigated water supply to minimize drought threats for a spate irrigation system. The novelty of study is development of a methodology for estimation of water holding capacity for reservoir by using geo-informatics tools. The objectives of paper are i. to demarcate the potential catchments of spate irrigation system and ii. floodwater storage by siting reservoir with geo-informatics tools. As an auxiliary output, a geo database is generated for intend to use its attribute data and spatial data for future research projects. This geo database include data layers of satellite imagery, GPS aided ground control points, irrigation network, catchments, administrative boundaries, proposed reservoir site location and digitized linear and polygon features. The results of this study depict that agricultural water management would be carried out efficiently with the use of developed methodology. The reliability of proposed reservoir solution is higher due to the use of high resolution datasets.

Keywords: Hill torrents, flood water management, spate irrigation, Remote Sensing, GIS.

Introduction

Sustainable irrigated agriculture is dependent on cost effective approaches to conserve the water resources[1] whereas spate irrigation systems are considered as risk-prone[2]. Risk in the semi-arid regions is due to long periods of drought and undedicated variability in rainfall runoff and distribution[3]. In Pakistan, spate irrigation is carried out on 1.4 M ha (10 % of canal irrigated area) and is the largest system of world[4]. This information leads to investigate sustainable managing practices for areas of spate irrigation by using more sophisticated approach through GIS.

Spate irrigation is associated with water management of mountainous catchments (hill torrents) in arid regions[5]. This system is a reliable form of water harvesting systems[6] but it differs significantly from controlled surface and groundwater irrigation systems. Variability of flows in space and time is the salient feature of spate irrigation and predictability of flows is difficult, as floodwater comes from large size catchments located in Pakistan[7]. In the lowlands, the floods are diverted to adjacent irrigable lands by means of diversion structures and then conveyed by distribution canals to the series of fields[8]. Flood flows of hill torrents have potential prospects for development to meet growing demands of water for agriculture in Pakistan[9]. In fact, these hill torrents have a lot of potential for agricultural development, if managed wisely. To harvest this potential through traditional system of floodwater diversion through earthen bunds is not reliable[10]. Moreover, the total crop water requirement is more than double than annual rainfall, it is obvious that to secure agricultural productivity secondary source of irrigation is needed[11]. It is, therefore essentially paramount to conduct research for the improvement of traditional system and to develop the sustainable system for the use this water potential as irrigation. This paper discusses GIS and Remote Sensing tools application as a strategy to explore this kind of prospective for study of floodwater management for spate irrigation, and to evade the possible hazards caused by these floods.

The problem of the area is that these hill torrents bring in flashy floods of shorter duration and high peaks[12]. Due to steep gradients, hill torrent flood flows with high velocities, which result in damages to standing crops, irrigation system, and infrastructure[13]. The fundamental problem is the optimal conservation of hill torrents flows i.e. the management of water resources of these hill torrents[9]. The spate irrigation system has been functioning quite satisfactorily for a longer period of time in study area of D.G. Khan but in recent past, due to accumulation of sediments in irrigation channels[5] caused uneven distribution of water in the main channels and created serious problem for overall management of the system. Due to silt deposit, the capacity of the spate water channels has reduced and cannot carry the excessive flood discharges and water overspill the banks which causes the loss of water and also prove damaging source for the crops. Current scenario indicates that there is dire need to update and improve GIS based datasets at the command area and field levels which is very crucial for sustainable crop production system. Therefore, to tackle the problem a detailed study for reservoir site selection is carried out.

In this study, we present cost effective approach to mitigate the flood hazard while conserving this floodwater to provide as irrigated water supply to minimize drought threats for a spate irrigation system. The novelty of study is development of a methodology for estimation of reservoir water holding capacity by using geo-informatics tools. The objectives of paper are i. to demarcate the potential catchments of spate irrigation system and ii. floodwater storage by proposing reservoir with GIS based estimation of storage capacity. As an auxiliary output a geo-database is generated for intend to use attribute and spatial data for future planning for development projects. This geo-database include data layers of satellite imagery, GPS ground control points, irrigation network, catchments, administrative boundaries, proposed reservoir site location and digitized linear and polygon features.

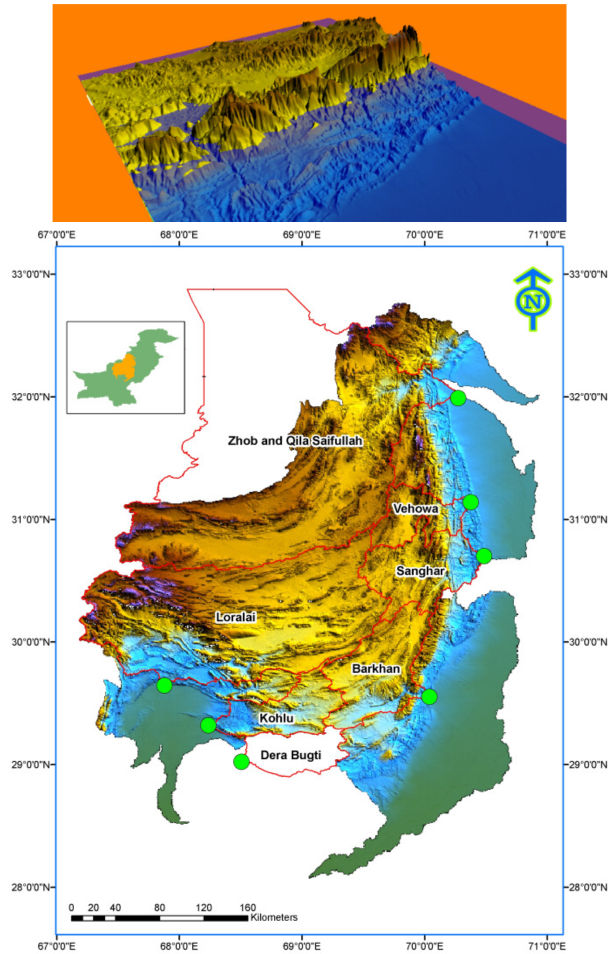

Figure-1
Defining study area at regional level using visual aid in 3D module

Material and Methods

Study area: The extent of study area is mainly divided into two levels i. regional local and ii. local level. The reason to adopt this strategy was to control the budget of study by using optimized financial resources to determine the cost effective methodology.

Regional level study area: Study area at regional level consists of 115,230 km2 covering four provinces of Punjab, Sindh, Baluchistan and Khyber Pakhtun Khwa (KPK) of Pakistan. The selection was done through dynamic visual aid of Digital Elevation Model (DEM) at 3D module of global mapper software application (figure 1). Further for precise demarcation under natural boundary conditions this area was delineated using basin tool in Arc GIS. To find runoff accumulation, the hilly area was divided into sub-catchments using a digital elevation model and a GIS[14]. As the study area is not confined of any administrative boundary, instead it is defined by the mountainous catchment area. It has potential for spate irrigation development as spate water coming from uphill have dissolved nutrients15 and it would be assume that more agricultural yield will be available.

A study in the arid mountainous region to explore the spate irrigation potential has been conducted earlier[16]. However, this study was mainly based on field surveys and mapping details. The value addition of current research study is that it is based on both the use of mapping details and geo-informatics tools.

Study area at local level: The spate irrigation is directly linked with hill torrents. The Vehowa hill torrent in D.G. Khan has 2634 km^2 catchment area with average discharge of 85,000 cusec and the command area is 122 km^2 (figure 2). This hill torrent has caused losses of Rs. 45 million, Rs. 130.6 million and Rs. 150.30 million during floods season of 1973, 1975 and 1976[17]. It would be considered that that if these floods were controlled at upper catchment, the amount of damage would be lesser.

The climate of the Vehowa is extremely hot and dry[18] with an average annual rainfall of 300 mm. The temperature, humidity, evaporation and rainfall during the critical period from January to June are shown in (figure 3).

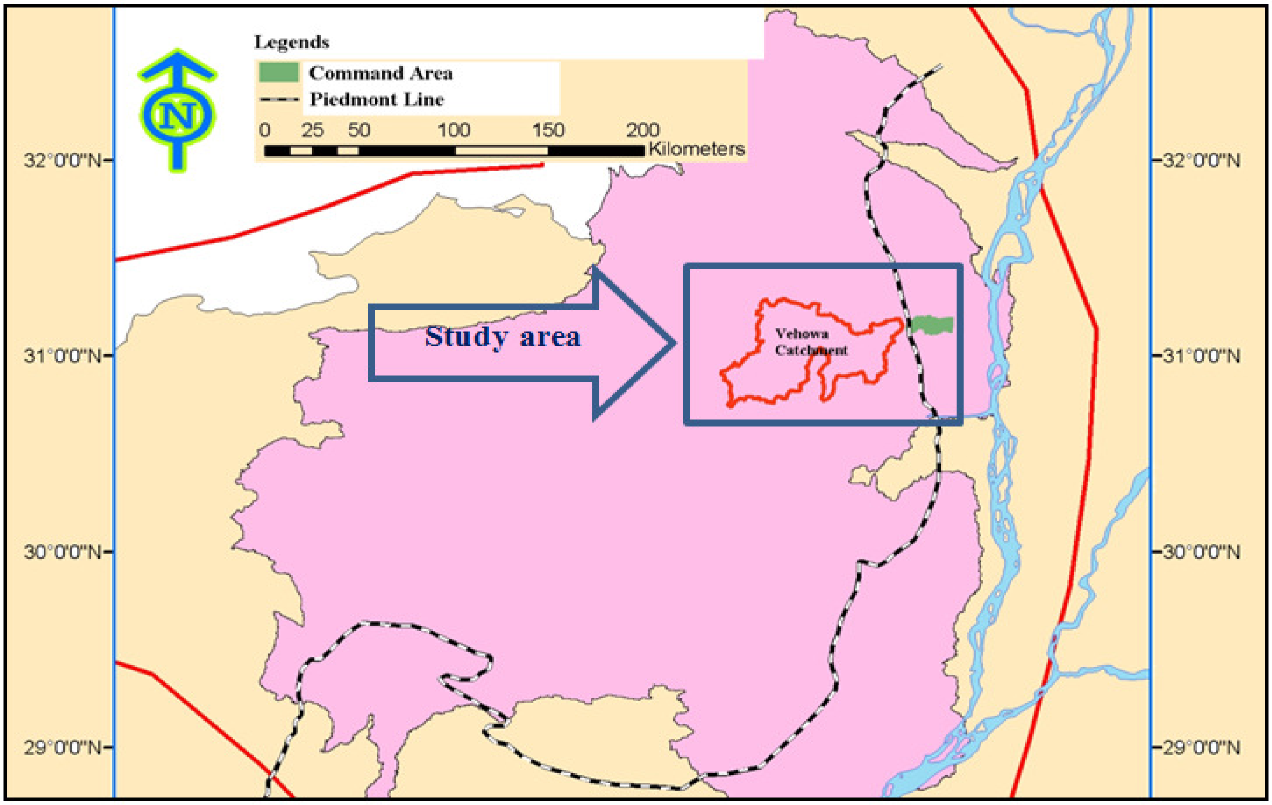

Figure-2
Local level study area with its catchment and command area

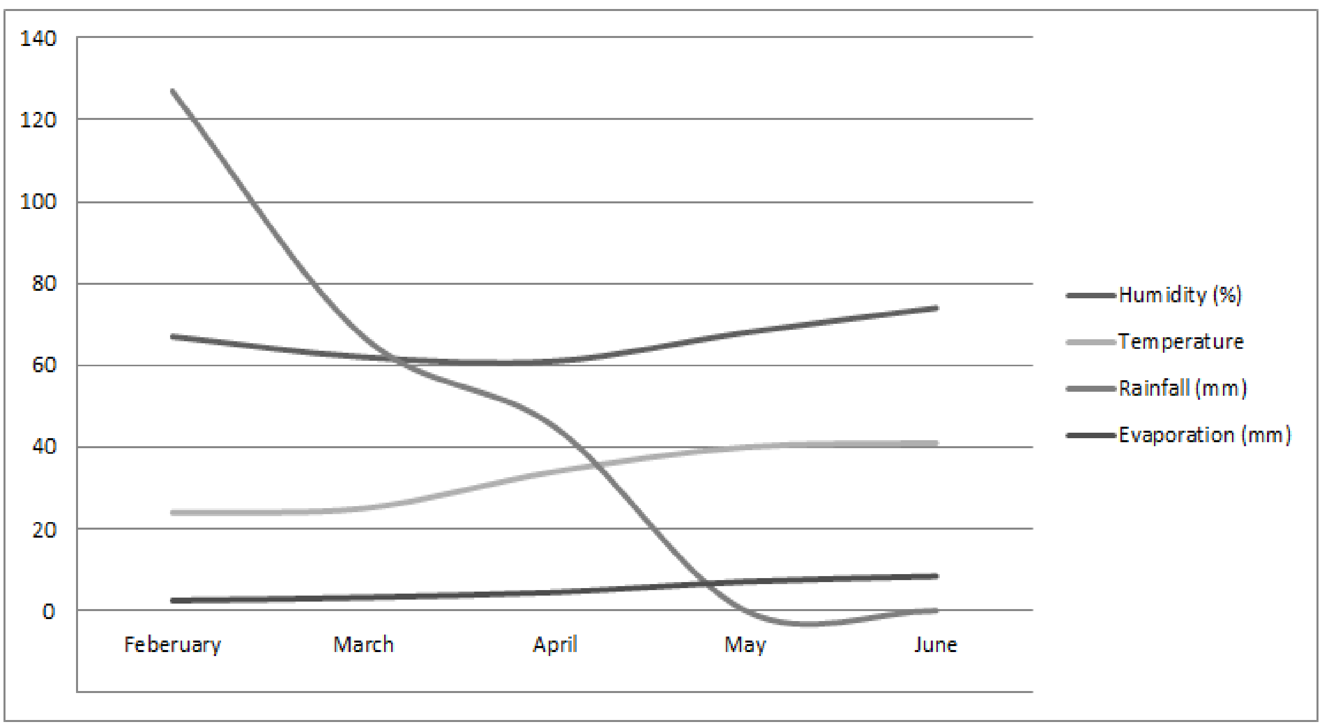

Figure-3
Temperature, humidity, evaporation and rainfall at Vehowa, D. G. Khan

Spate mechanism: The typical spate mechanism is depicted in (figure 4)[16], floodwater rush towards low height grounds. This water is normally causes flash floods but it fully depends upon the localized terrain. Before it enters to agricultural fields, it is divided and diverted. This study assumes that if terrain of hill torrents is digitally analyzed then more preferred solutions would be available. The (figure 4) clearly convey its idea if we have full information of the elevations then different kind of flood control structures sites would easily be define. It means more information, more sustainable irrigation system.

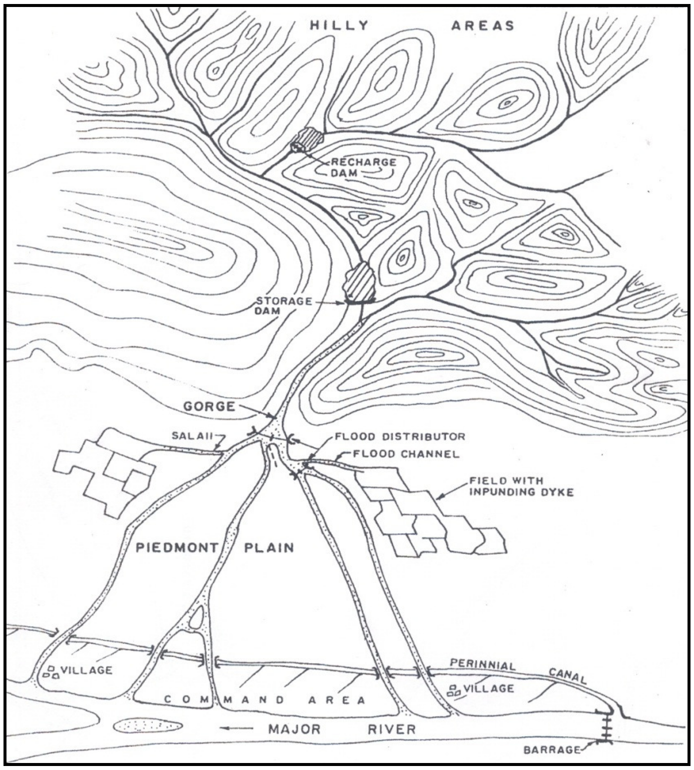

Figure-4
General concept of hill torrents and spate mechanism

Datasets and specifications: The specifications of datasets used in the research work are provided in (table 1). The procedural details of operations and purpose of use are discussed under stepwise methodology.

Table-1
Datasets specifications and sources

Data type	Specification
Base map	Scale (1: 250,000)
GPS data	Point data through ground survey
SPOT imagery	2.5 m resolution
Landsat TM imagery	30 m resolution
Topography sheet	1:250,000
Shuttle Radar Topography Mission (SRTM)	3 arc resolution
Soil map	1:500,000
Hydrological map	1:500,000
Land cover data	Shapefile

Quality and authenticity of datasets: As the main operation is done on SRTM based Digital Elevation Model (DEM), therefore data authenticity description would lead to ensure the quality of output results. SRTM was a joint project between the National Imagery and Mapping Agency (NIMA) and the National Aeronautics and Space Administration (NASA), United States of America. The SRTM obtains elevation data on a near-global scale to generate the most complete high-resolution digital topographic database of earth[19,20]. Under this mission, digital topographic data for 80% of the earth's land surface, with data points located at every 30 x 30 meters (1-arc-second) on a latitude / longitude grid to 3-arc-second. The 3-arc-second SRTM data has been used for this study to development DEM.

The base map of the D.G khan and mountainous region of local level study area provides the information to identify the target areas of interest. The map is of large scale i.e. 1: 25,000 however additional features identification was done using SPOT 2.5 m resolution image of Vehowa, D.G. Khan. The satellite image of Landsat TM (30 m resolution) was used for land use classification acquired by the secondary source (Water Resources Research Institute). The land cover data was also used at regional level study area in the format of shape file. The hydrological map and soil map were used to digitize the ground water potential and to define land productivity classes respectively at local level study area.

Research guide indicators: The research guide indicators which were proved to be helpful during the development of methodology and to define the scope of research work are presented in (table 2). It was important to mention that these research guide indicators are extracted points from literature review.

Table-2
Research guide indicators with references

Research guide Indicator	Research
Spate irrigation is a floodwater harvesting and management	21
Water sharing in spate irrigation system is its salient feature.	22
There would be wrong application of traditional water right due to the changing cropping pattern.	23
Construction of check dams to slow down the flood velocity and to trap the sedimentation.	24
To find reservoir location, its feasibility analysis and design parameters calculation using GIS is sophisticated technique.	9
Soil and water conservation practices are widely applied on highlands	25
Investigating the potential for different water management techniques in spate irrigation system using the spate management model and its use for decision making	26

Mapping: For the integration of information (satellite images, maps digitization) geo-referencing and clipping were performed to prepare and integrated base information (figure 5).

Geo-database layers preparation: In GIS based analysis geo-database is very important therefore it is very important to have a well-developed geo-database structure to exploit allof the GIS analysis functionality[27]. Figure 6 (a) describes the catchment and command area overlaid by two layers of satellite image and groundwater availability. Similarly (figure 6b, c) demonstrates the elevation model in 3D and color ramped theme respectively. Figure 6 (d) shows drainage network in the catchment area. Data layers shown in (figure 6a, d) were prepared using Arc GIS application while (figure 6b, c) with global mapper application software. These layers were analyzed to identify the reservoir location where floodwater would be store and to minimize the threats of flood damages.

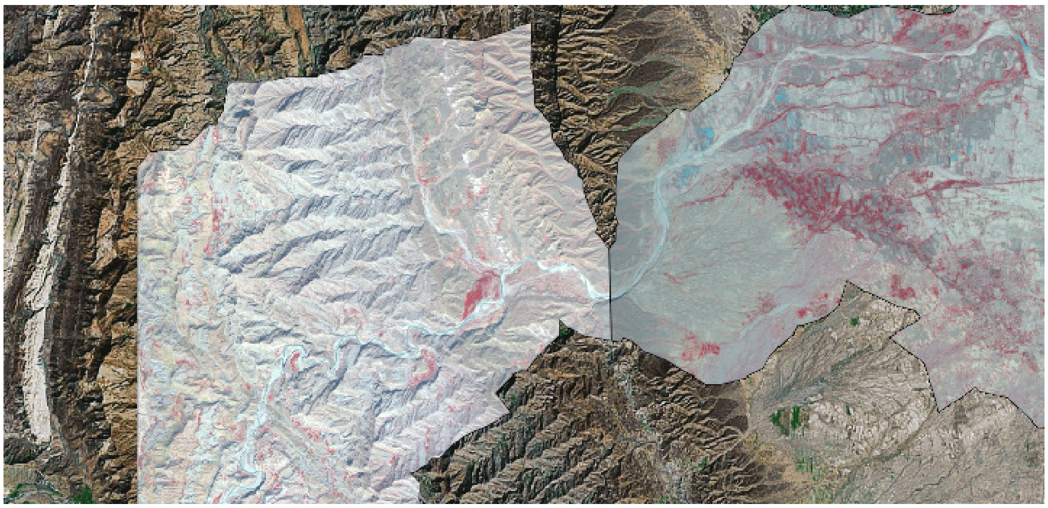

Figure-5
Geo-referenced images overlay and demarcating prominent feature at agricultural field level

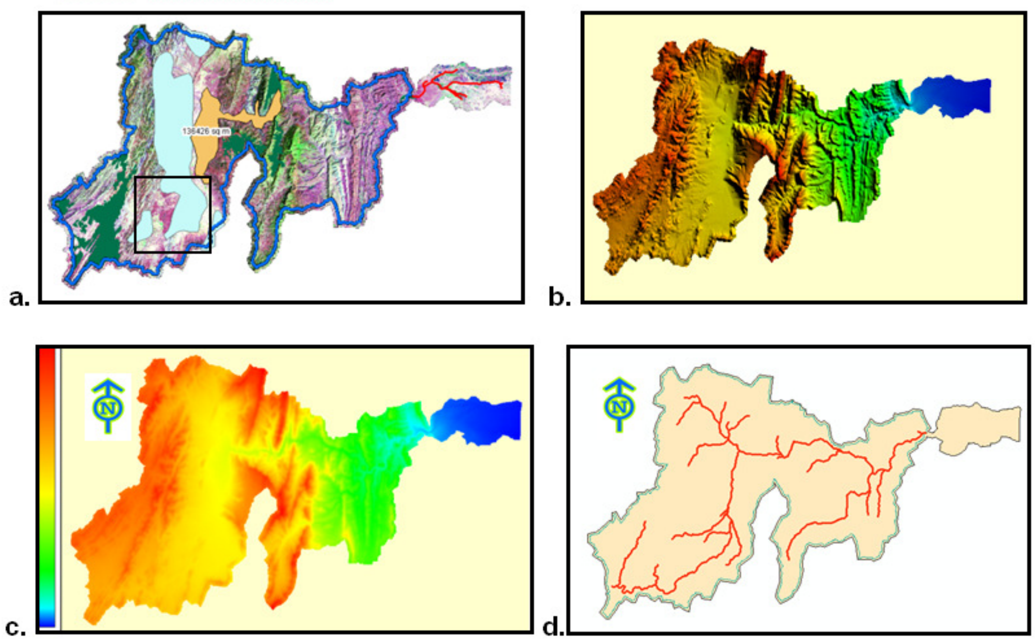

Figure-6
a. Dam and groundwater potential, b. observing DEM flatness in command area, c. color ramped DEM and d. drainage pattern in catchment area

Ground based survey with GPS was conducted and important ground points were arranged and an elevation profile was generated (figure 7). This profile would help to determine floodwater depths at different locations.

Reservoir siting and capacity analysis: All layers of geo-database were merged with elevation model in 3D module of global mapper and location of reservoir was identified. At different options of reservoir height relevant dynamic scenarios were generated. Each scenario came up with its submerged area under water (figure 8). The submerged area at 1270 m height from the datum line was captured as an image in 3D module. Then this image was geo-referenced with the Vehowa DEM (figure 8a). The submerged area was digitized and the Vehowa command area DEM was clipped using this geo-referenced digitized submerged area boundary (figure 8b, c).

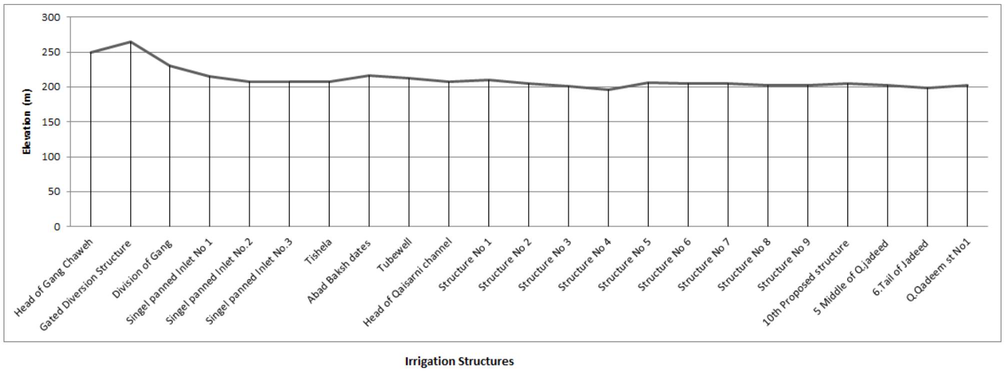

Figure-7
Profile generation along agricultural structures with GPS

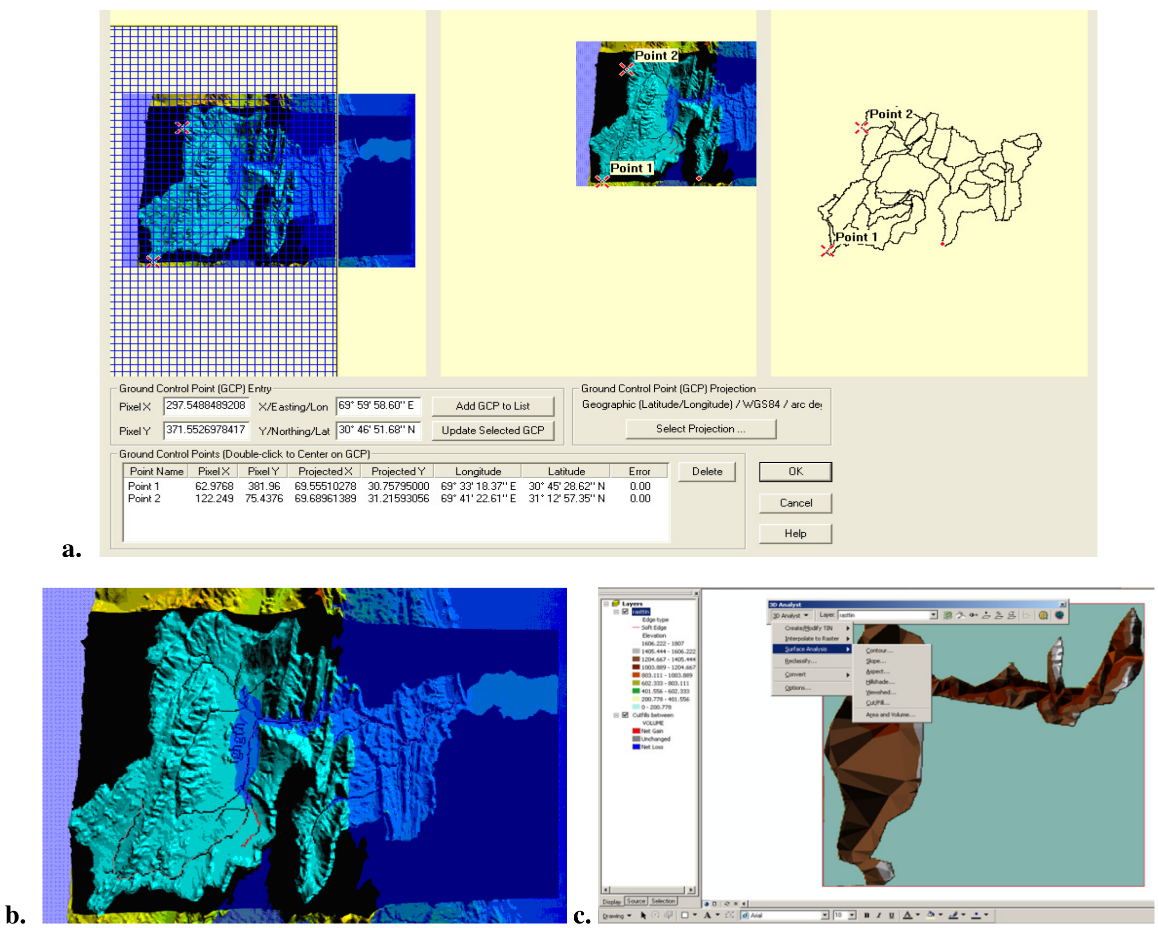

Figure-8
Reservoir capacity calculation and selection of site location using geo-informatics tools

Using Arc GIS, the DEM terrain was used to calculate gross storage capacity of the dam. For proposed reservoir height of 1270 meters from datum line, calculated water holding capacity of reservoir was 1.73 Million m^3. To prepare full inventory of the reservoir, gross storage capacity change under different water level below 1270 meters were calculated and graphically presented in (figure 9).

Results and Discussion

Sustainable irrigation system: During past decade, several study reports on spate irrigation by local and foreign experts have been prepared[13,28,29]. These reports addressed various aspects of hill torrent flood management. In 1984 National Engineering Services Pakistan (Pvt) Ltd. (NESPAK) prepared a study entitled "Flood Management of D.G. Khan Hill Torrents". In 1992 Japan International Cooperation Agency (JICA) completed another study "development of irrigation based upon flood flows of D.G. khan hill torrents"[30]. In this study JICA improved the base line data and updated the study of NESPAK. In this paper, further fine tuning is attempted for management practices of floodwater to make agriculture more sustainable. (figure 10) describes the major results of this paper. A reservoir with an elevation of 1270 m with gross capacity of 1.73 Million m^3 is proposed and it is assumed that after development of this reservoir it will be able to combat the drought and flood threats for spate irrigation system. However, increased population is a limiting factor for the development of agriculture based economy. Large tracts of land in the hill torrent areas are lying unproductive due to lack of irrigation facilities. The patchy and erratic pattern of rainfall does not support the agriculture sector. Only a limited part of hill torrent areas is commanded by flood irrigation and is dependent upon occasional runoff generated by natural precipitation. Under this scenario, current study would contribute for the benefit of agriculture sector.

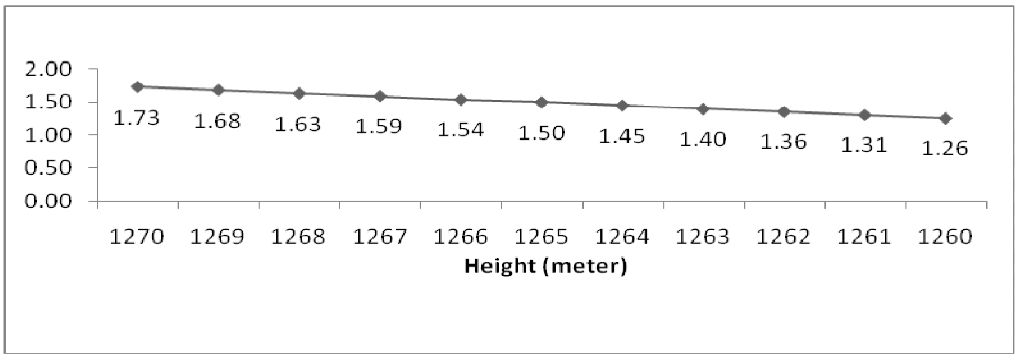

Figure-9
Reservoir storage capacity calculations (BCM) per unit change in height

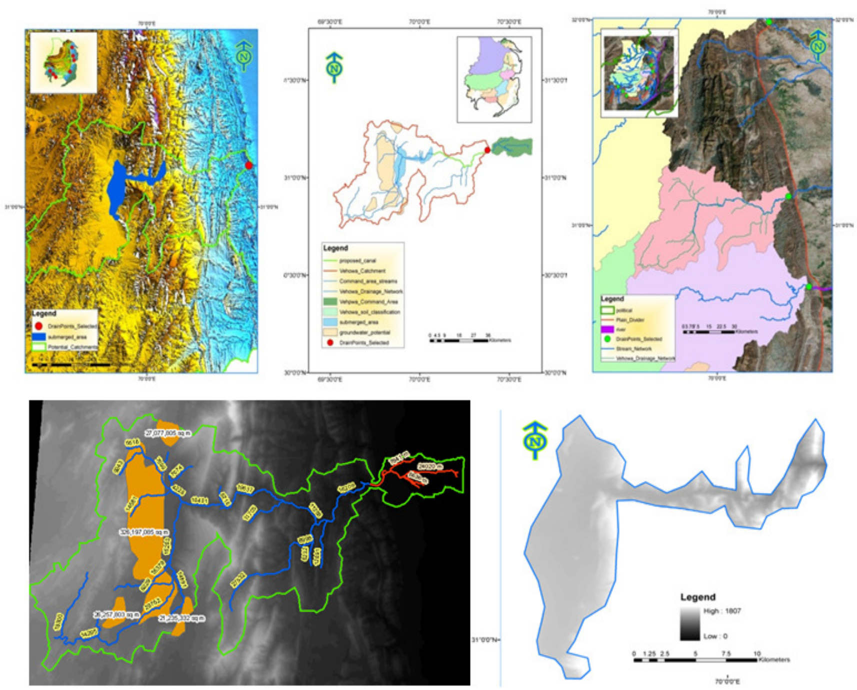

Figure-10
Integration of layers for potential site possibilities

Precise demarcation of catchments: A precise demarcation of potential catchments (figure 11) of spate irrigation system was completed at GIS platform. This digital information would be a source for future developments and research activities and this data will be used for master planning for spate irrigation system which is second phase of this research work.

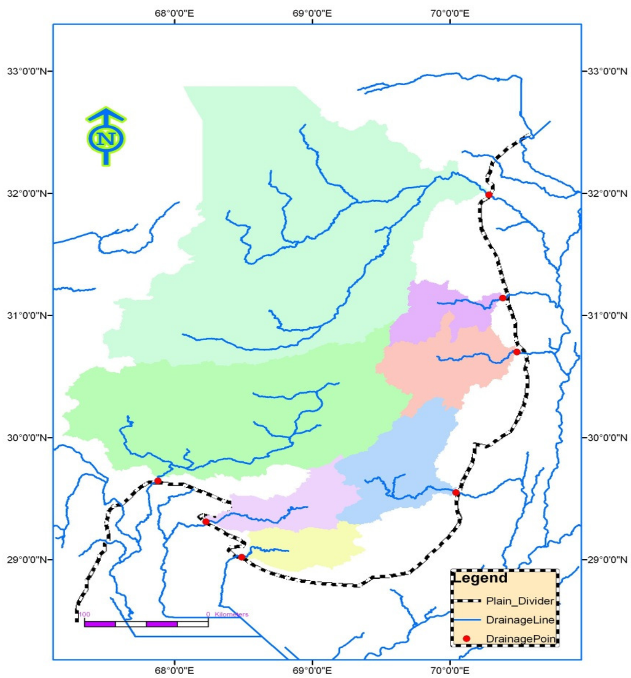

Figure-11
Precise demarcation of potential catchments for spate irrigation

Impacts of dam on agriculture: The management of flood flows for agricultural development essentially requires a comparative study of pre and post project level of production. The historical cropping pattern based on revenue record of D. G. Khan would be used to estimate the after effects due to development of proposed floodwater storage reservoir. The runoff Vehowa catchment if trapped with the proposed reservoir then existing cropped area would be increased moreover it can also assume that yield per acre will also increase. It is a fact that man needs to conserve the water resources and to manage water system for efficient use. This need is growing more due to population increase. Resultantly, a sustainable and manageable spate agricultural system would be a solution to minimize the gaps between demand and supply of agricultural products.

This study outlines a procedural approach using GIS and remote sensing techniques to identify potential site for harnessing floodwater for command area. The used datasets includes satellite imagery, topographic sheets, ground survey and developed geo-database. The digitized irrigation network would be suitable to locate potential sites for field structures as an improved strategy for development and up gradation of irrigation water network.

Conclusion

The main purpose of this study was to harness floodwater for improved agricultural productivity and development of the study area through better water management practices under economical ways. The results of this study depict that agricultural water management would be carried out using geo-informatics tools and developed methodology is a new contribution for the estimation of storage capacity with integrated tools of Arc GIS and global mapper software applications.

In any kind of research study, the main discussion focuses on reliability of the results and it is directly linked with the accuracy and authenticity of the input datasets and applied procedure. However the reliability of proposed reservoir is higher due to the use of high resolution image (2.5 m spatial resolution) and use of more refined methods of data operations like careful and precise geo-referencing, GPS data integration under consultation of the field experienced experts of Water Resources Research Institute (WRRI) of National Agriculture Research Center.

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