Indian Journal of Science and Technology, *Vol 11(26), DOI: 10.17485/ijst/2018/v11i26/126945, July 2018*
ISSN (Print) : 0974-6846
ISSN (Online) : 0974-5645

Application of GIS and Statistical Methods for Design of Dams for Water Supply and Flood Control: A Case Study of Virgin River Basin, Utah State, USA

Hamid Mohebzadeh[1*], Amirmassoud Fathi[2], Seyed Mohammad Safaeddin Abolmoali[2] Shahram Navabi[2] and Farzin Abbasi[2]

[1]Department of Water Engineering, Faculty of Agriculture, Bu-Ali Sina University, Hamedan, Iran; hamidmohebzadeh@gmail.com
[2]Department of Civil Engineering, Roudehen Branch, Islamic Azad University, Roudehen, Iran.

Abstract

Objectives: To propose new concept based on combination of GIS and statistical methods as a decision support tools for estimation of dam dimensions, reservoir volume and area. **Methods/Statistical analysis:** To accomplish this goal, firstly spatial data analysis on GIS was used to select the best location along the river for construction of the dam that has enough capacity for storage of required volume of water. Then Peaks Over a Threshold (POT) techniques was utilized to estimate 150-year flood discharge using daily discharge data from 1991 to 2013; and a simple overfall spillway was designed to release surplus waters from the reservoir. **Findings:** Results of GIS spatial analysis showed that a dam with crest height of 84m and length of 339m could be constructed that has a reservoir with 50.7 MCM storage capacities and surface area of about 1.44 km^2. Combination of GIS and POT method reveals that after release of surplus waters from the reservoir by the spillway, reservoir volume rises up from 50.7 to 51.6 MCM (increase about 900000 cubic meters). This is volume of the 150-year flood that can be stored in reservoir of the dam after release of surplus waters by the designed spillway. **Application/Improvements**: This study concludes that combination of GIS and statistical analysis is a powerful tool for finding the most appropriate situation for dam construction compared with reservoir surveys method.

Keywords: GIS, Peaks over a Threshold (POT), Flood control, Dam construction, Reservoir volume and area

1. Introduction

The growths in water requirement make essential building of dams for water storage. At the present stage, the most important reason for attention in reservoir systems is mainly owing to their application for flood control, irrigation, fishing, hydro-electric power, and etc. Generally, dams are used for two common purpose, firstly as a water resources system and secondly as an essential paramater in water resource management[1]. The amount of water, which can be reserved in a reservoir, is called reservoir capacity or storage capacity. However, this value relies on the volume of water inflow to and outflow from the reservoir. In[2] declared that the tolerable usage of the nonrenewable water resources is constrained mainly due to insufficient information about the amount of accessible water resources and shortage of proper water resource management. This justifies the demand to build the capacities of reservoirs utilizing cheaper techniques. Direct (reservoir mapping) and indirect methods (use of topographical maps) are the most used methods for reservoir characteristics calculation. Generally used methods for estimation of water surface area in reservoirs, like field survey, are very expensive since they are highly tedious and time consuming[3]. Geographic Information System (GIS) due to easy processing, analysis and manipulating of spatial data has extensively utilized in hydrological studies. GIS propose a robust set of tools for illustrating and testing spatial relationships. Generally, GIS can be utilized for making

**Author for correspondence*

persuading graphics, which interact between the analytic results and the spatial formation of data with force and clarity. The superiorities of utilizing DEM among GIS are to produce flow direction, flow accumulation, aspect, slope, flow path, elevation, and drainage network maps quicker and exactly in comparison to the usual traditional cartographic techniques[4].

Dams in addition to the fact that are noteworthy resource can also be a source of danger for downstream societies with dam failure probably causes inadmissible damage to belongings and loss of life. The most significant reason for dam destruction is the overtopping of dams due to insufficient flood carrying capacity. Thus, design of flood control structures that storage specific volume of a flood with certain return period to prevent overtopping and possible failure of the dams is a significant parameter. Flood peak and flood frequency analysis are always important parameters in flood-related analyses in order to accurately estimate flood that are required for many designs such as structural flood control or management-related studies[5]. Methods used for the selection of design floods in different countries vary and are contained either in recommendations and guidelines (issued by professional bodies) or even in legislation[6]. Peaks over a Threshold (POT) models have been frequently employed for the study of flood frequency analysis. The observations of time series of environmental factors (e.g. wind, rainfall, temperature, discharge, sea level, sea surges), however, represent powerful temporal autocorrelation. Classically, in order to choose independent events for the mentioned statistical analysis, the hypothesis of a physical threshold to prevail for defining an "Extreme event" was largely utilized, and the POT sampling widely spread in the literature[7]. In this study, we used this method for flood frequency analysis.

The aim of this work is to use GIS and statistical methods as a decision support tools for design of dams with specific volume of water and estimation of the water surface area in reservoirs after occurrence of design flood in rivers. For this purpose yearly water volume of Virgin River in south of Utah state was calculated and a dam with appropriate height was designed in suitable location of this river to storage this volume. Design flood was estimated with POT method and proper spillway was designed for storage and detention of this flood in reservoir. Then, changes in storage volume of the dam were calculated after controlling the flood by the spillway. Results depict that GIS can be utilized as a robust tool to prepare practical approach for water policy makers and managers. Reservoir volume and area can be analyzed for various dam situations in a simpler way compared with reservoir surveys methods to find the most proper situation for the dam establishment.

2. Materials and Methods

2.1 Study Area

The study was carried out in the Springdale catchment, which is located in the virgin Basin on the Utah state, USA with area of approximately 1086 km^2. The Virgin River flows between Kane and Washington counties in Utah and enters into Arizona state in south of Utah. The Springdale catchment is demarcated by latitude 37° N to 37°30" N and longitude 112°30" W to 113° W. There is no any dam in this catchment and we selected it to determine a suitable location for construct a hypothetical dam to use it in calculations. Figure 1 shows location of the study area in Utah State.

2.2 Data Acquisition

Digital Elevation Models (DEM) is the essential information to estimate the volume of the reservoir. Suitable computation of storage capacity requires high resolution DEM (5 meters or finer). For this purpose, 5-m resolution DEM of the study area was downloaded from UTAH automatic geographic reference center official web site. The DEMs have been created from the imagery collected during the 2006 NAIP and HRO aerial photography flights.

Flood frequency analysis by POT method requires hourly or daily river discharge. For this purpose daily discharge data of the Virgin River from October 1991 to October 2013 provided by U.S. Geological Survey (USGS) station 09404900 were used in this study. This station located in the western part of the study area (Figure 1). Minimum and maximum measured discharge in this period is respectively 0.73 m^3/s and 60 m^3/s and average of daily discharge is 1.61 m^3/s.

2.3 GIS Scheme for Calculating Flooded Area and Storage Capacity

This section provides a brief description on GIS techniques for calculating flooded area and storage capacity. When a dam is built in an area, upstream regions will be flooded

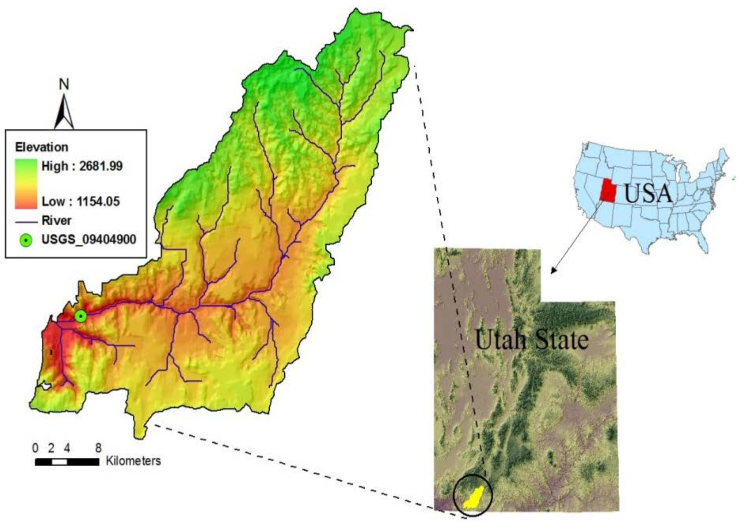

Figure 1. Location of the study area in Utah State

up to a specific water level. Topographic information and water surface elevation of the reservoir, generated by the dam, are the crucial information for calculation of the flooded area and stored water volume in reservoir of the dam, which can be computed by utilizing the spatial data analysis on GIS. After designation of the dam dimensions like location, height, freeboard and the designed water level H, to specify the flooded upstream a raster map comprising one pixel in the mentioned area is created and is utilized for the iteration as the starting point. Estimation of the flooded area can be accomplished using iteration with propagation so long as there is no change to any further extent in the pixel values. By this approach, pixels in the DEM, which have higher altitude compared with desired water level H will be specified as undefined. Else, pixels that do not satisfy this condition, will dedicated the maximum value of 9 values detected by a proximity matrix, which moves upon the elevation map. There exists just one starting pixel in the initial iteration, which is assigned by the operater as 'True'. Afterwards in every subsequent iteration, the adjacent pixels to the True pixel(s) will be assigned 'True' if they have altitude less than desired water level H. With this procedure, area upstream of the dam that will be flooded to desired water level H is calculated. Figure 2 describes this scheme.

After calculation of flooded area, storage capacity can be found as follows: firstly, the storage depths are computed by subtracting the elevation of the DEM from the designed water level H, and afterwards summing up the storage depths based on the grid cell and multiplying

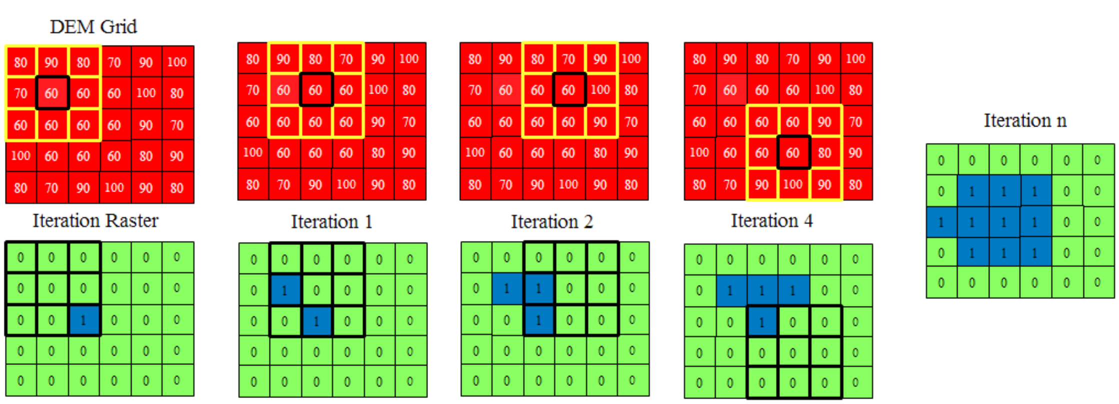

Figure 2. Conceptual scheme of calculating flooded area after construction of a dam with water level 60

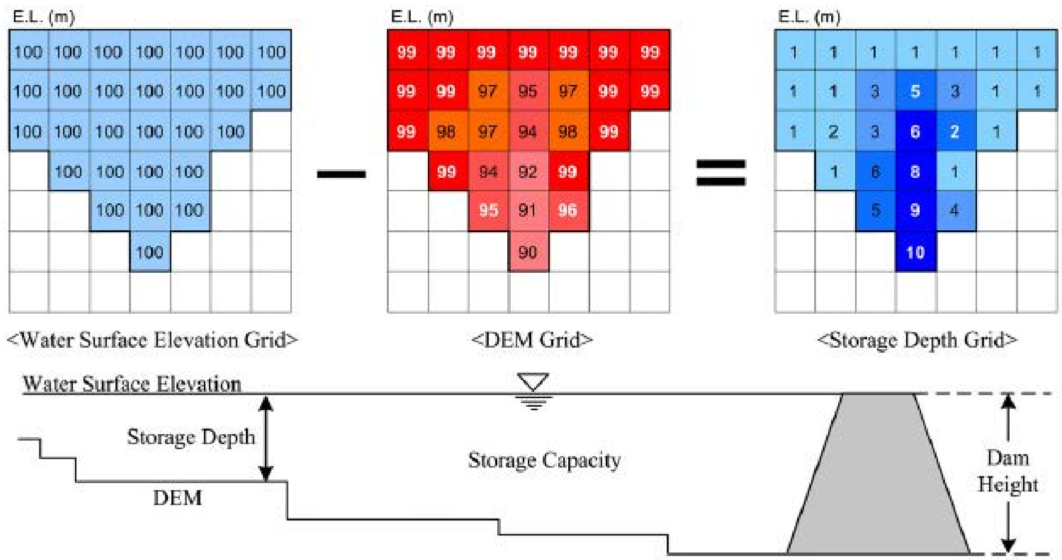

Figure 3. Conceptual scheme of calculating water volume[13]

them by the area of the unit cell. This scheme has been described in Figure 3. In this study, ILWIS 3.3 GIS software was used for calculation of flooded area and storage capacity of the reservoir after dam construction.

2.4 Statistical Analysis

As mentioned earlier in this research POT was utilized for flood frequency analysis. For this purpose POT package which is an add-on package for the R statistical software[8] was used. The fundamental objective of this package is to develop tools to perform statistical analyses of Peaks over a Threshold (POT). The basic concept of the most functions used in this package is based on the Extreme Value Theory (EVT) that briefly describes as follows:

Let $X_1,\ldots, X_n$ be a series of independent and identically distributed random variables with common distribution function F. Suppose $M_n = \max(X_1,\ldots, X_n)$. Assume there exists normalizing constants $a_n > 0$ and b_n such that:

$$\Pr\left[\frac{M_n - b_n}{a_n} \le y\right] = F^n(a_n y + b_n) \rightarrow \mathrm{G(y)}, \qquad \mathrm{n} \rightarrow +\infty \qquad (1)$$

For all $y \in \mathbb{R}$, where G is a non-degenerate distribution function. Based on the Extremal Types Theorem, G should be Fréchet, Gumbel or negative Weibull. In[9] declared that these three distributions can be incorporated into a single parametric family: the Generalized Extreme Value (GEV) distribution. The GEV has a distribution function defined by:

$$G(y) = \exp\left[-\left(1+\xi\frac{y-\mu}{\sigma}\right)_+^{-1/\xi}\right] \qquad (2)$$

Where (μ, σ, ξ) are the location, scale and shape parameters respectively, $\sigma > 0$ and $z_+ = \max(z, 0)$. The Fréchet case is determined when $\xi > 0$, the negative Weibull when $\xi < 0$ while the Gumbel case is defined by continuity when $\xi \rightarrow 0$[10].

In[11] demonstrated that the conditional survival distribution of exceedances (or peaks, or excesses) $X - u$ over an enough high threshold u, given $X \geq u$, is a generalized Pareto distribution (GPD).

$$1 - G_u(x,\gamma,\sigma) = \begin{cases} \left\{1+\dfrac{\gamma(x-u)}{\sigma}\right\}^{-1/\gamma}, & \mathrm{x} \in (\mathrm{u},\infty) \quad \text{if} \quad \gamma > 0 \\ \exp\left\{-\dfrac{(x-u)}{\sigma}\right\}, & \mathrm{x} \in (\mathrm{u},\infty) \quad \text{if} \quad \gamma = 0 \\ \left\{1+\dfrac{\gamma(x-u)}{\sigma}\right\}^{-1/\gamma}, & \mathrm{x} \in (\mathrm{u},\mathrm{u}-\dfrac{\sigma}{\gamma}) \quad \text{if} \quad \gamma < 0 \end{cases} \qquad (3)$$

Where the parameter γ is the extreme value index (EVI) and is a basic value in the literature of extreme value analysis. Its symptom is a significant factor in illustrating the tail of the underlying distribution F(x). To perform the adequate estimators $\hat{\gamma}$ and $\hat{\sigma}$, an input of u is required, and this is a very open topic choice. Given a value of u, the estimation of the GPD parameters can be performed in a variety of ways that a popular method is maximum likelihood (more details have been described by[12].

After estimation of 150-year flood discharge, the estimated discharge was considered as the design flood and a simple overfall spillway was designed to calculate changes in storage volume of the dam after controlling the flood by the spillway. The discharge equation of the overfall spillway can be written as follows:

$$Q = g^{\frac{1}{2}} b C_d H^{\frac{3}{2}} \tag{4}$$

Where Q is discharge (m^3/s), g is gravity acceleration (m^2/s), b is the spillway length, C_d is coefficient of discharge (dimensionless) and H is the head on the spillway (m).

3. Results

3.1 Dam Construction and Calculation of Flooded Area and Storage Capacity

The average daily discharge measured by USGS station 09404900 is 1.61 m^3/s that means the annually water volume in this river is approximately 51 MCM. This volume was considered as initial storage capacity for design of a dam in this river. To build a dam the engineers must first select a location along the river that has suitable cross-section and the dam reservoir made in this location has enough capacity for storage of required volume of water. For this purpose, 3D view of the river basin for visual selection of a suitable cross section was created by DEM of the area. Several cross-sections were considered along the river and a dam was constructed in every cross-section. Storage volume of dams was calculated by ILWIS and the most suitable cross-section was selected with attention to minimum length and height of constructed dam that was able to storage required volume of water. Procedure mentioned above led to selection of a suitable cross section with bed elevation and top elevation of 1225 m and 1320 m, respectively (Figure 4).

After choosing of the dam situaiton, reservoir volume and area was calculated for various dam crest heights at the location of the dam to specify the suitable height of the dam. In this study, neighborhood operations in ILWIS were used to determine the exact area to be flooded. For this purpose, firstly new raster map, which henceforth called DAM, was made utilizing value domain on the DEM and height of the dam dedicated to all cells on this map. Then these two maps were integrated using following equation:

DE Medited = IFF (ISUNDEF (DAM), DEM, DAM)

According to this expression if a pixel is not defined in map DAM, then the value of the DEM is assigned to the pixel, otherwise the value given in map DAM. Therefore, the altitude of the dam is placed in the Digital Elevation Model. To specify flooded area a map was created indicating one pixel in this zone. Utilizing proximity operations this pixel operates as the starting

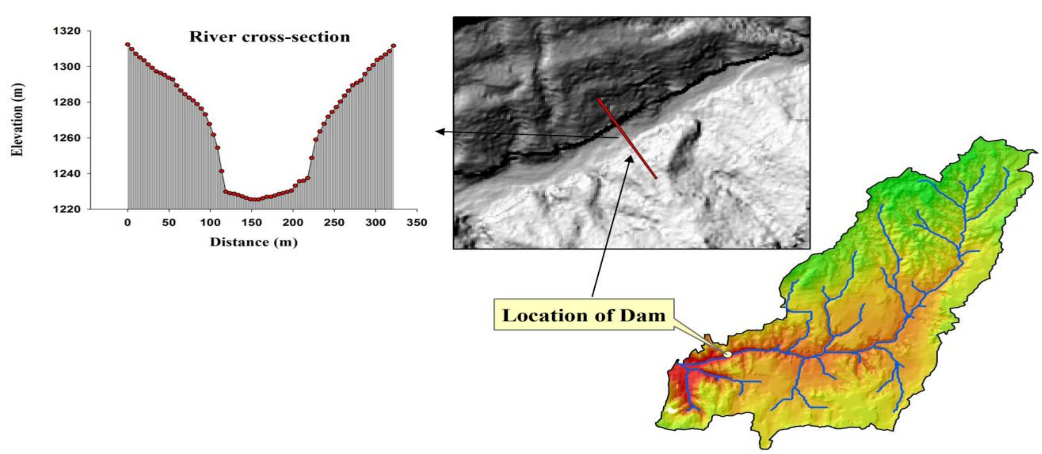

Figure 4. 3D view of the riverbed with location of the cross-section and cross-section profile

point for the computation, which value below dam height defined TRUE and otherwise FALSE using bool domain. Iteration with propagation was applied as far as pixel values remained without any change. The output raster map of this approach outlines the number of cells filled with water. For estimation of the reservoir volume cross operation carried out between generated raster map and DEM that was made as number of TRUE cells and DEM elevation values. The cross table is obtained which depicts the integrations of input values of the raster map and DEM (Table 1, a part of the Cross Table).

Eventually, depth of water in reservoir was extracted by subtracting the height of every pixel of DEM from the designed water level H and these depths were multiplied by pixel area to obtained volume of water in each pixel. Water volume was calculated from cumulative of the pixels, which filled water. This procedure was repeated several times for different dam heights to obtain the optimum dam height that in this height reservoir storage capacity is about 51 MCM, approximately. This work led to establishment of a dam with crest height of 84 m (elevation of 1309 m, msl) and length of 339 m that has a reservoir with volume and area of 50.7 MCM and 1.44 km^2, respectively (Figure 5).

Graphic of reservoir capacity-area has been generated using Ilwis graph menu. Figure 6 represents the relationship between two 'parameters' 'Surface area' and 'Capacity' of reservoir as obtained from GIS calculations.

Table 1. Cross table of DEM and number of TRUE pixels

	Flooded	Dem with dam site	Number of Pix	Area	Depth	Volume
1*1226	1	1226	28	700	83	58100
1*1227	1	1227	140	3500	82	287000
1*1228	1	1228	154	3850	81	311850
1*1229	1	1229	238	5950	80	476000
1*1230	1	1230	309	7725	79	610275
1*1231	1	1231	182	4550	78	354900
1*1232	1	1232	185	4625	77	356125
1*1233	1	1233	195	4875	76	370500
1*1234	1	1234	254	6350	75	476250
1*1235	1	1235	289	7225	74	534650
1*1236	1	1236	260	6500	73	474500
1*1237	1	1237	293	7325	72	527400
1*1238	1	1238	259	6475	71	459725
1*1239	1	1239	307	7675	70	537250
1*1240	1	1240	340	8500	69	586500
1*1241	1	1241	363	9075	68	617100
1*1242	1	1242	479	11975	67	802325
1*1243	1	1243	494	12350	66	815100
1*1244	1	1244	544	13600	65	884000
1*1245	1	1245	453	11325	64	724800
Min	1	1226	28	700	0	0
Max	1	1309	1057	26425	83	1325700
Avg	1	1267.5	688	17205	41.5	604404.4643
StD	0	24.393	253	6333	24.393	338891.4252
Sum	84	106470	57808	1445200	3486	50769975

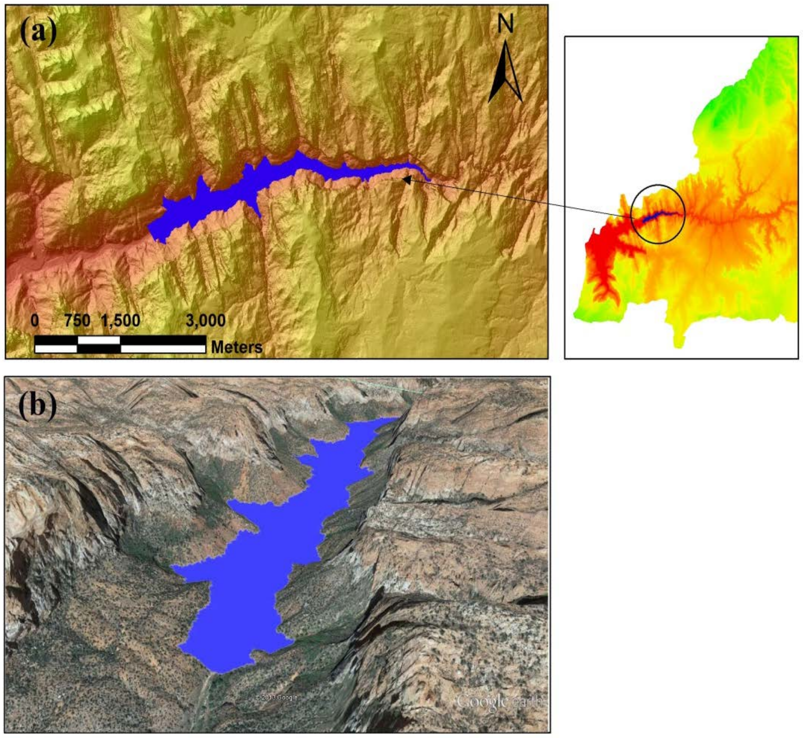

Figure 5. (a) Upstream flooded area after dam construction; (b) 3D view of the flooded area in Google Earth

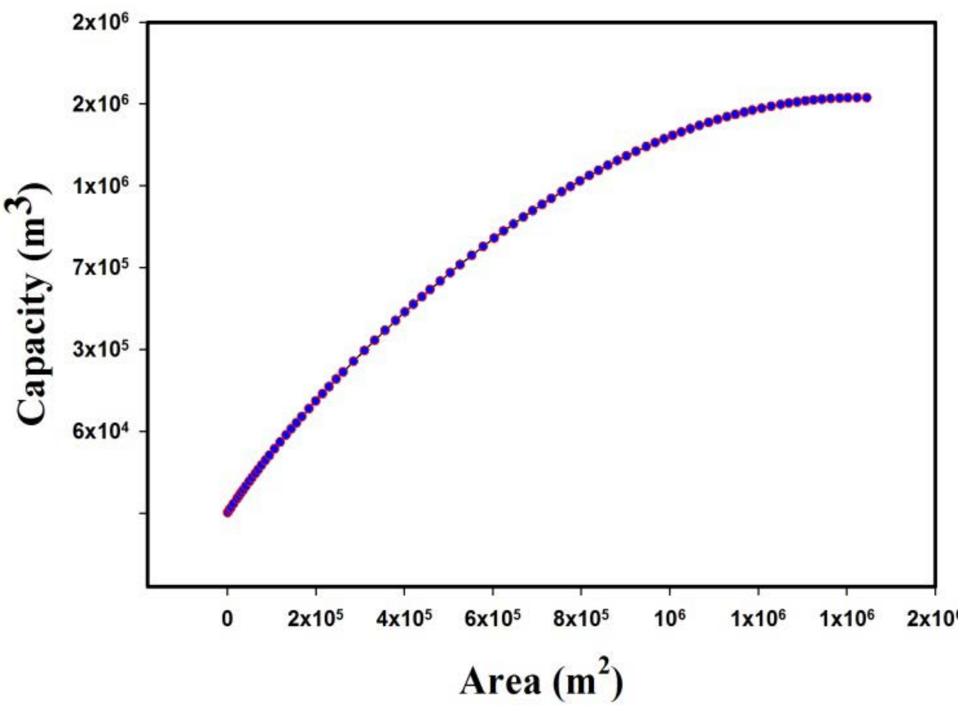

Figure 6. Graph showing general relationship between capacity and area for the reservoir

3.2 Change in Storage Capacity after 150-Year Flood Occurrence

After construction of the dam, we supposed that if a flood with 150-year return period occurs in the river and we designed a simple spillway to discharge excess waters from the reservoir in order to prevent overtopping and probable damages to the dam, the storage volume and flooded area after flood occurrence how much will change? For this purpose, discharge of 150-year flood was estimated by POT package. In flood frequency analysis a specific statistical series is developed based on the defined variable and an appropriate Statistical distribution is fitted on this series to estimate the magnitude or frequency of flooding. Usually

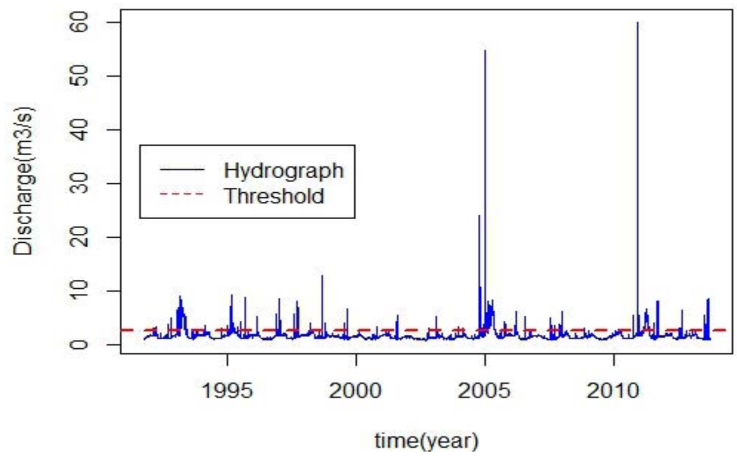

Figure 7. Daily discharge from 1991 to 2013, used for the threshold selection

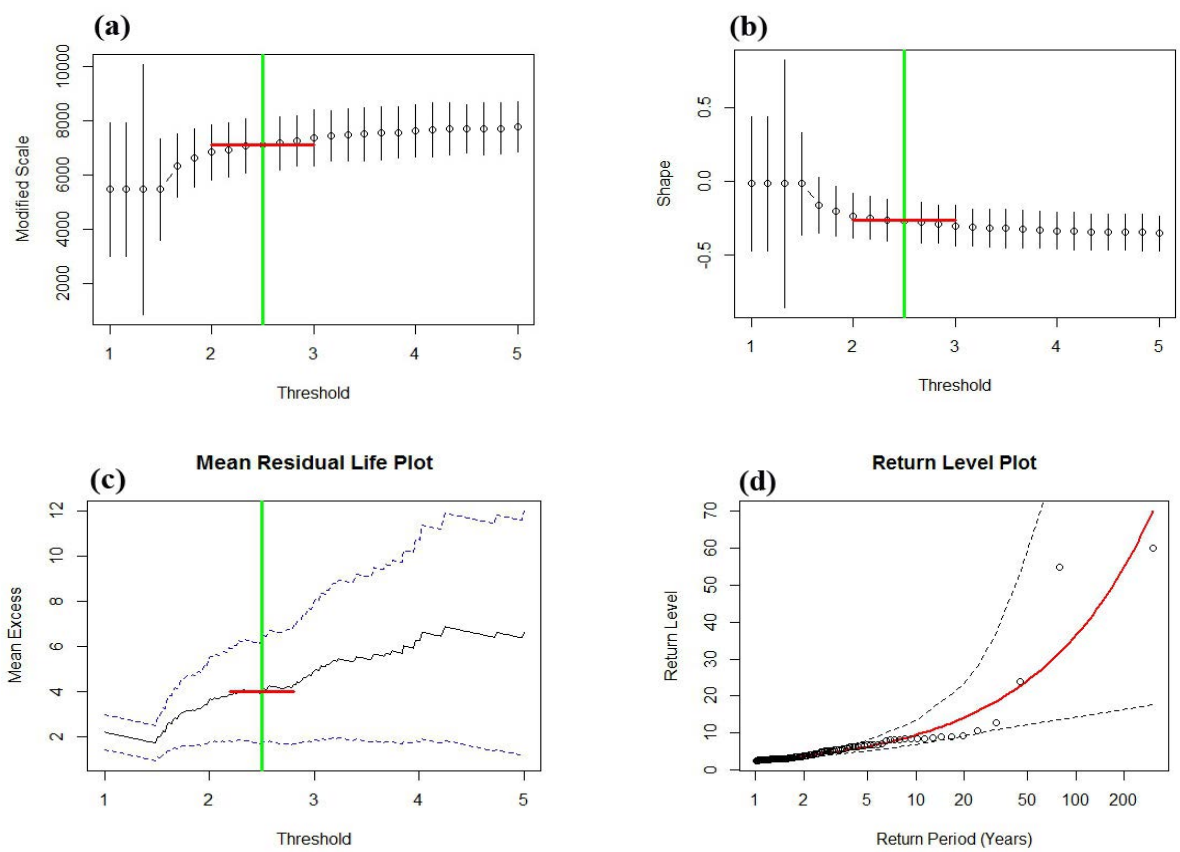

Figure 8. POT graphics. (a-b) threshold selection using the Threshold Choice Plot function; (c) threshold selection using the Mean Residual Life Plot function; (d) Return Level Plot

all of points are not used for developing Statistical series and there are some approaches for extracting the extreme data. An alternative is to define an overall threshold. The major objective of threshold selection is to choose adequate events to decrease the variance. In this study a reasonable threshold ($2.5 m^3/s$) was selected by POT package tools for threshold selection (Figures 7-8 (a, b, c)). Then maximum likelihood estimator was used for estimation of generalized Pareto distribution (GPD) parameters. Finally, return level plot was created by fitting GPD function on exceedances of a threshold (Figure 8(d)) and return level of 150-year flood was estimated approximately $118 m^3/s$.

After estimation of 150-year flood discharge, we considered it as design flood and a simple overfall spillway was designed to release excess waters from the reservoir and changes in storage volume of the dam were calculated after controlling the flood by the spillway. We assumed a spillway length of 100m and a constant discharge coefficient of 0.75 to storage and detention the dam while a flood with discharge of $118 m^3/s$ occurs in upstream of the dam. Thus, the head on the spillway was calculated 0.65 m using Eq. (4). This head was used for calculation of storage volume changes after flood occurrence. Results showed that after release of surplus waters from the reservoir by the spillway, reservoir volume rises up from 50.7 to 51.6 MCM (increase about 900000 cubic meters). This is volume of 150-year flood that can be stored in reservoir of the dam after release of surplus waters by the designed spillway.

4. Conclusions

GIS was found to be a suitable tool to determine reservoirs area and volume. This means that after building of a dam, volume and area of the reservoir can be calculated without the need to carry out extensive field surveys. In general, the paper provides a method to which a water manager is able to predict the volume of t-year flood that can be controlled by design of a flood control structure. Surface area of storage volume map was computed utilizing ILWIS 3.3 GIS software and capacity-area graphic was presented. 150-year flood discharge was estimated by POT method and changes in storage volume after controlling the flood by the spillway were calculated.

In this study, we have focused on applying GIS as a collection of powerful tools for construction of dams with required storage volume and other factors, which will affect site suitability, such as economic efficiency, site accessibility and site geology, were not taken into account.

5. Acknowledgements

The author is thankful to Utah automatic geographic reference center and United States Geological Survey for providing data used in this study.

6. References

1. İRVEM A. Application of GIS to Determine Storage Volume and Surface Area of Reservoirs: The Case Study of Buyuk Karacay Dam. International Journal of Natural & Engineering Sciences. 2011; 5(1):39-43.
2. Mugabe F, Hodnett M, Senzanje A. Opportunities for increasing productive water use from dam water: a case study from semi-arid Zimbabwe. Agricultural Water Management. 2003; 62(2):149-63.
3. Sawunyama T, Senzanje A, Mhizha A. Estimation of small reservoir storage capacities in Limpopo River Basin using geographical information systems (GIS) and remotely sensed surface areas: Case of Mzingwane catchment. Physics and Chemistry of the Earth, Parts A/B/C. 2006, 2006; 31(15);935-43.
4. Tribe A. Problems in automated recognition of valley features from digital elevation models and a new method toward their resolution. Earth Surface Processes and Landforms. 1992; 17(5):437-54.
5. GO G, Harmancıoğlu N, Gül A. A combined hydrologic and hydraulic modeling approach for testing efficiency of structural flood control measures. Natural hazards. 2010; 54(2): 245-60.
6. Novak P, Moffat A, Nalluri C, Narayanan R. Hydraulic structures. 4th Edition. CRC Press. 2007. p. 1-736.
7. Cunnane C. Methods and merits of regional flood frequency analysis. Journal of Hydrology. 1988; 100(1): 269-90.
8. R: a Development Core Team R: A Language and Environment for Statistical Computing. Ver. 2.15.2. R Foundation for Statistical Computing. Vienna. 2011.
9. Jenkinson AF. The frequency distribution of the annual maximum (or minimum) values of meteorological elements. Quarterly Journal of the Royal Meteorological Society. 1955; 81 (348):158-71.
10. Ribatet M. A User's Guide to the POT Package (Version 1.4). Department of Hydrological Statistics, INRS. 2006.
11. Pickands IIIJ. Statistical inference using extreme order statistics. The Annals of Statistics. 1975; 3(1):119-31.
12. Wong TST, Li WK. A threshold approach for peaks-over-threshold modeling using maximum product of spacings. Statistica Sinica. 2010; 20:1257-72.
13. Yi C-S, Lee J-H, Shim M-P. Site location analysis for small hydropower using geo-spatial information system. Renewable Energy. 2010; 35(4):852-61.