Optimization of Rainwater Harvesting Sites using GIS

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Abstract: Water scarcity is hitting new peaks every day and is exacerbated by the current rapid climatic change. Demand for clean water in India is very high, especially for agriculture and consumption. One way to cater to these needs is through rainwater harvesting. Through this paper, we propose a framework that optimizes the site selection for reservoirs by intersecting various data points. Our framework uses a three-step approach to combine stream networks, digital elevation, and soil quality to produce the most viable reservoir sites. Our framework is easy to implement and highly scalable. For the purpose of this paper and a proof of concept, we restrict our focus to the arid Beed district in the state of Maharashtra, India. Our approach provides consistent results that are corroborated by the manual inferences that can be drawn from the data under consideration.

1 INTRODUCTION

India is a large and diverse country. Its exponential progress is tethered down by problems like water scarcity and floods. Due to over-exploitation of water resources, many of our freshwater sources are getting depleted. Groundwater is not getting recharged. The persistent water shortage issue and intense droughts could be mitigated through large scale rainwater harvesting.

The aim of our project is to create an accurate, and adaptable system which would provide better decision making, and easier planning, when laying out any plans for rainwater harvesting. Hydro-logical planning should take into account the amount of rainfall an area receives, the groundwater and soil conditions, land use and land cover and water requirement. Potential sources for rainwater need to be identified. We intend to use data from various sources, such as Topographical Maps, 3D terrain models, meteorological data, administrative data, etc. This data will be merged to simulate water conservation structures such as reservoirs, canals, dams, etc.

The idealistic aim for the project is to make a system efficient enough to serve India with the objective of careful use of water resources and optimization to increase the water harvesting capacity. The framework and methodology followed can be used universally for the purpose of demonstration. We have concentrated on the Beed and Nagpur district of Maharashtra, which often suffers from droughts.

Figure 1: Map for Beed district.

Figure 2: Map for Nagpur district.

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2 MOTIVATION

Clean, potable water is a requirement for all land-based biological activity. However, in the past few years, there is a decreasing amount of water available for humans to consume because of multitude of factors such as unpredictable rainfall, droughts, over-utilization of wells, inefficient farming techniques, etc.

Most of Maharashtra faces drought crisis during the monsoon season. The drought in 2013 was considered as the region's worst drought in 40 years. The worst-hit areas in Maharashtra were Solapur, Parbhani, Sangli, Pune, Satara, Beed and Nashik. Beed, a district in central Maharashtra, suffers with a serious drought crisis. In 2015, Beed (G Seetharaman, 2016) received less than 50 per cent of its average annual rainfall of 670 mm. The previous year had only been slightly better with 55.6 per cent of the average rainfall. This has affected the groundwater level in the district. Beed, along with Osmanabad and Latur, is the most waterstarved in the Marathwada region where the state government has declared droughtlike conditions. According to a recent Press Trust of India report (Press Trust of India, 2016), there is only 5 per cent water in Marathwada's dams. Beed collector Ram says the government spent around Rs 80 crore in 2015-16 on water conservation projects in the district. In 2018 (TNN, 2018), districts in the state have been declared as drought-prone.

Hence, we introduce simulation based modelling and optimization, to increase the efficiency, and water harvesting capacity of these efforts. The system can potentially play an important part in making appropriate decisions to lay out water-harvesting resources, and thus increase the amount of water available to people.

3 REVIEW OF LITERATURE

This paper (Jasrotia et al., 2009) suggests a study of the water resources. The water balance study using the Thornthwaite and Mather (TM) models with the help of remote sensing and GIS found out the moisture deficit and moisture surplus for an entire watershed. It showed that the maximum annual runoff resulted from the built-up areas/water body followed by agricultural land, dense forest and minimum for the barren land and open forest. GIS software had been used for spatial analysis of various thematic layers and integration to produce the final runoff map. After the runoff map was produced, it was found that suitable sites for rainwater harvesting structures accounted only for a fraction of the actual watershed area whereas the rest of the area was unsuitable site for rainwater harvesting.

This paper (Mahmoud and Alazba, 2014). says that the very first step in rainwater harvesting is to trap the rainfall where it falls. To accomplish this, a geographic information system (GIS) based decision support system (DSS) was implemented, which focused on developing a methodology to suggest potential sites for in-situ water harvesting (IWH) considering factors such as rainfall, slope, potential runoff coefficient (PRC), land cover/use, and soil texture.

Another research study made use of GIS and Remote Sensing to delineate potential sites for rainwater harvesting. This methodology (Kumar et al., 2008). carried out their research in the districts of Uttar Pradesh. They used thematic maps consisting of land-use/land-cover, geomorphology as layers along with geology and drainage integrated with the GIS system. The maps were weighted by importance and multiplied with the ranked features of each site. An average score for each of the features was obtained and integrated into the GIS system for inference.

Here, (Ziadat et al., 2012) applied a GIS approach for identifying the suitability for rainwater harvesting interventions in Jordan. They integrated biophysical criteria such as slope, vegetation cover, soil texture, and soil depth with socio-economic parameters such as land owner and then modified the criteria. Each criterion was assigned one of two ratings: best or second best. These ratings provided more flexibility for determining the suitability of an intervention.

This paper (Naseef and Thomas, 2016) used thematic maps and soil cover to determine optimum locations for rainwater harvesting in the state of Kerala near the Kechri river basin. Aster Digital Elevation Model (DEM), Rainfall data are needed for this study. Daily rainfall data of all stations situated in and near Kecheri river basin was obtained. The thematic maps used in this study are Landuse map, Classified slope map, Stream order map, Runoff potential map and Soil permeability map.An overlay of these features is obtained using an appropriate GIS system to get the desired locations.

4 METHODOLOGY

The system consists of two major components, that need to be related. The features of the terrain are processed, along with perennial stream networks to determine watershed regions, and their capacity. Data about soil type and quality is factored in to ensure that i) regions with less porous soil are used to reduce

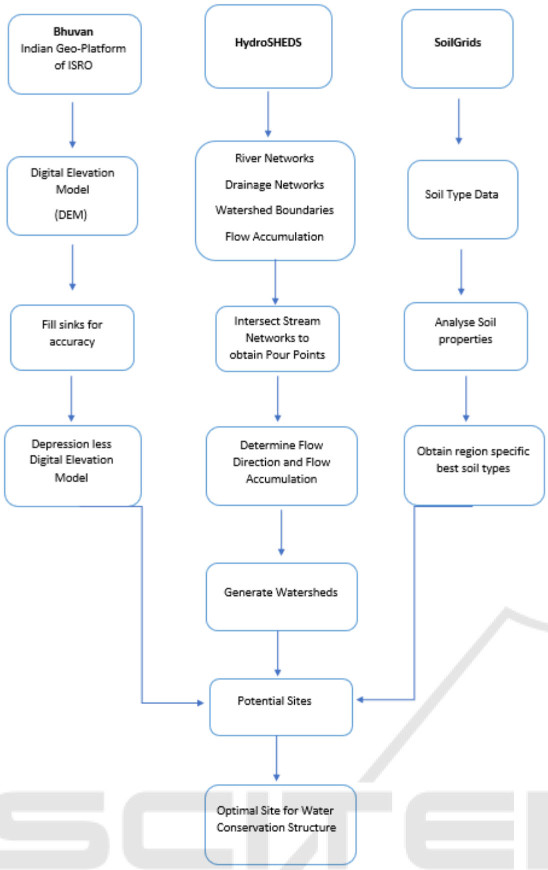

Figure 3: Overview of system architecture and processing.

seepage loss, and ii) less cropland is converted for rainwater harvesting purposes. These features provide us a way to estimate the utility of each watershed region as a potential site for rainwater harvesting.

Data about the terrain can be obtained in various forms, but we chose a Raster Digital Elevation Model (DEM), as it is universally obtainable for nearly all regions, improving repeatability of the method. Hydrological conditioning of the DEM is performed to reduce error in watershed delineation. Once the watersheds are delineated, the terrain is analyzed over several metrics, to obtain an aggregate score for each watershed. These scores are then used to recommend the watersheds in which rainwater harvesting systems should be constructed.

4.1 Hydrological Conditioning

The process of hydrological conditioning is performed as follows:

1. A depressionless DEM is created by filling in sinks.
2. Flow direction is computed for every raster cell.
3. Flow accumulation is computed for every raster cell.
4. Points of intersection of the perennial stream network are used as pour points.

4.2 Watershed Delineation

The outcomes of hydrological conditioning, namely the depression-less DEM, the Flow accumulation raster, and the pour points are used to delineate the watersheds in the manner described in (Susan K. Jenson, 1988).

4.3 Metrics

Site suitability cannot be decided without taking the method of rainwater harvesting into account. The chief method of rainwater harvesting in rural India, especially rural Maharashtra is through the creation of small-scale mud reservoirs, or embankments around one or more sides of a natural basin. These are known as 'bunds'. These bunds are inexpensive to build, require materials that are locally available, and are easy to build. Therefore, we have devised the following metrics taking the needs of bund-based rainwater harvesting into account.

The metrics we have chosen to use are explained below.

4.3.1 Watershed Capacity

We normalize the capacity of the watershed per unit area to remove bias towards large watersheds. This capacity is calculated by estimating a given level of precipitation over the area, and computing the water retained at the surface, using the slope characteristics, and infiltration potential of the soil. This metric is computed over several levels of precipitation, and a weighted average is computed as the final score.

$$Capacity = \sum_{i=1}^{n} \sum_{j=1}^{levels} \frac{retention_j \times infiltration_j}{slope_j \times precipitationlevel_i}$$

4.3.2 Watershed Density

For rainwater harvesting systems, it is favourable if the storage capacity of the watershed is concentrated over a smaller area as compared to a larger one. This would permit the pooling of resources over a smaller area, reduce evaporative and ingress losses, and enable farmers to use check-dams on natural depressions. This is computed by calculating the ratio of the total surface capacity of the watershed to the surface area it is spread over. This is done for multiple levels of precipitation, and a weighted average is computed for the final score.

$Density = \frac{Capacity}{Area}$

4.3.3 Soil Characteristics

Soil Characteristics such as permeability, as well as regional crop suitability are taken into account. This allows us to ensure that fertile cropland doesn't get destroyed for these purposes, as well as to reduce ingress loss at the site.

The regions consist primarily of Calcisoils, Vertisols, and Kastanozems. Vertisols are moderately fertile, clayey, and have a low porosity. They are suitable for agriculture if properly maintained. The regions in question both have significant agriculture in these soil types. Calcisoils are mainly found in arid reigons, as the ones we see here, and are less suitable for agriculture. They are highly porous soils, due to their loose composition. Kastanozems are highly fertile, and humus rich. They are the most suitable for agriculture. Thus, for our purposes, Calcisoils are most suitable for rainwater harvesting, despite their porosity, as they are used for less agriculture. Vertisols are less suitable and are hence weighted lower. Areas with Kastanozems are small and used heavily for farming, so they are weighted the least. After analysis, we chose the weights 0.6, 0.3, and 0.1 for Calcisoils, Vertisols, and Kastanozems respectively.

4.4 Combination

The watershed metrics are combined by taking the weighted average of the watershed metrics above. Each soil type is a multiplier, computed on the basis of its permeability, and crop-suitability. This allows us to weight our overall suitability score by the product of the watershed score with the soil multiplier.

5 IMPLEMENTATION

The project is implemented in ArcGIS, as it is the industry-standard for GIS applications. Each process detailed in 4 has a corresponding ArcGIS implementation. The DEM data is the CartoDEM, created by the Indian Space Research Organization, obtained through its Bhuvan platform. It has a resolution of 1 arc second, which is equivalent to approximately 10m. It was published in May 2015. Stream networks were obtained through the HydroSHEDS Asia Stream Networks. It has a resolution of 3 arc seconds (90m at the equator). All datasets use the WGS 1984 spatial reference system.

The soil data was obtained through the ISRIC SoilGRIDS dataset. It is a global system for automated mapping of soil classes and properties at 250m resolution.

5.1 Hydrological Conditioning

The hydrological conditioning steps were performed using the corresponding ArcGIS tools, i.e. The sinks were filled in using the *Fill* tool, the Flow direction was computed using the *Flow Direction* tool, and flow accumulation using the *Flow Accumulation* tool. The pour points were obtained by intersecting the vectors of each individual stream, to obtain a set of intersection points, using the *Intersect* tool.

5.2 Watershed Boundaries

The watershed boundaries are computed using the Watershed tool.

5.3 Watershed Capacity

This was computed by estimating basin volume, minus the percolation amount, obtained through the runoff curve values. This gives an estimate of the true capacity of a given basin to retain water. This process is repeated multiple times to obtain a weighted average score.

5.4 Wateshed Density

This is computed by obtaining the resultant surface area of the waterlogged region, at varying water volumes. This process was repeated at several levels, and a weighted mean was taken.

5.5 Soil Characteristics

The soil data was obtained through SoilGRIDS, and each type of soil was manually analysed. Each coefficient was calculated, and assigned to a particular type of soil. Each watershed's total coefficient was calculated by weighting the areas of each soil type, with their respective coefficients, and dividing it by the total area of the watershed.

5.6 Final Score

The final score is computed as mentioned in 4.4. The suitability of the entire watershed is then visualized based on the score by assigning them colors on a spectrum of blue to red. Blue means high suitability, while red means low.

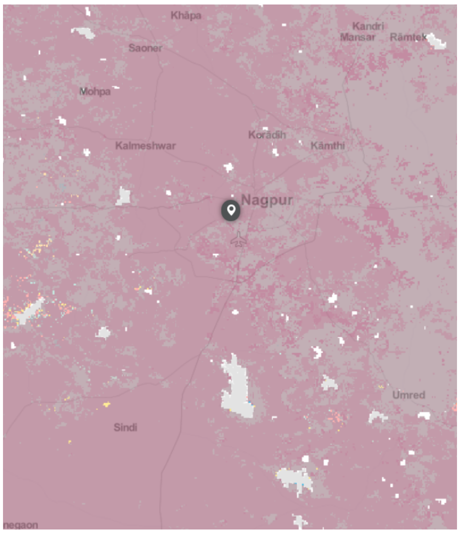

Figure 4: Soil Coverage in the Nagpur District.

Figure 5: Soil Coverage in the Beed District.

Watershed density was given the highest weightage, as a watershed with large capacity over a large area is not as useful for harvesting. However, too small a capacity is also detrimental, hence this term is also included in the score.

Since the region contains just a few soils, we performed a manual study of the soils and assigned weights according to their properties.

6 RESULTS AND DISCUSSION

Results generated for the Nagpur area using the described framework, along with the legend have been depicted in 6, 8 and 9. The results for Beed are depicted in 7. The generated results have been assigned a colour scale to make it easy to understand the degree of usability of the watersheds delineated. Here, we see that the gradation from dark blue to red indicate suitability from best to worst.

The suitability score has values in the possible range of:

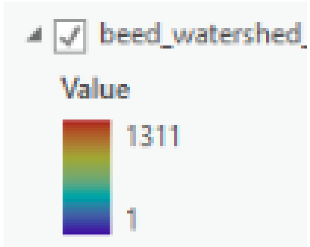

Figure 6: Site Legend.

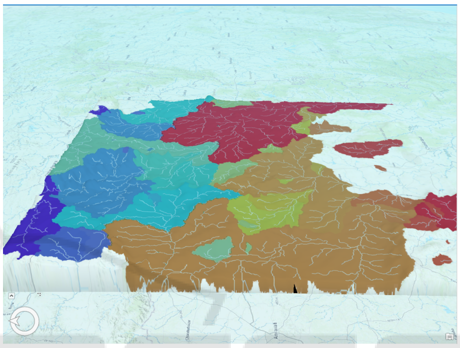

Figure 7: Results obtained for the Beed district.

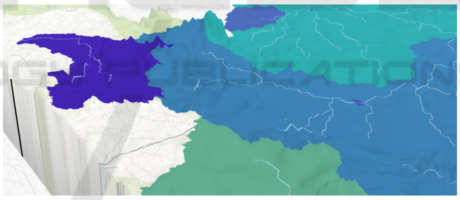

Figure 8: Best site for Rainwater Harvesting in Nagpur.

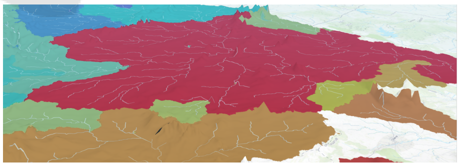

Figure 9: Worst site for Rainwater Harvesting in Nagpur.

The Marathwada region of India is a highly arid region with vast undulating planes. As such, the watersheds generated are much larger than average. Vertisols cover a vast majority of the area and have high water retention. Rainwater received in this area is significantly lesser than the required amount, especially for the largely agrarian occupations in the region.

By using permanent stream networks, we have provided a way to leverage perennial stream water and stream networks to find suitable watersheds. By relying entirely on satellite data, we have reduced the reliance on human data collection that is usually required for such a vast undertaking. Moreover, the location independent nature of the framework make it applicable to any area of the world, as long as there is satellite data available.

The results produced by our model have been able to make fairly consistent inferences pertaining to the construction of dams, canals at the requisite locations. Based on the satellite data found, the methodology has provided decent visualizations of the possible construction locations.

7 CONCLUSION

Our methodology can be used for any location and will provide results irrespective of the district of investigation. The algorithm requires three layers for reaching its conclusion - the DEM, hydrosheds and soil grids for a location specified by its latitude and longitude. Since the data is available for the whole country, the implementation can be reproduced for any location.

In terms of future scope, we could use this methodology on different districts in different parts of the country where the climate and soil conditions would be considerably different from those in the state of Maharashtra. Another improvement to the implementation would be to use topography data available from the Government of India which would increase the accuracy of the model, if used above the Digital Elevation Model.

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