Technobius, 2023, 3(1), 0034, DOI: https://doi.org/10.54355/tbus/3.1.2023.0034

Technobius

https://technobius.kz/

e-ISSN 2789-7338

Article

Dam Site Characterization Based on Land Use and Land Cover Changes in Urban Catchments. A Case of the Msimbazi Catchment in Dar es Salaam, Tanzania

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Abstract. Site characterization is crucial for the location and design of dams because it offers data for risk assessments and the planning and implementation of remediation measures. This study looked into the potential use of GIS-based methods for the characterization of dam sites. Satellite pictures were used to verify the catchment delineation results. The catchment slope, the number of networks in the sub-basin, and the land surface cover were all taken into consideration while choosing a location for a dam. From the findings, five possible dam site locations — Kisarawe (upstream), Magomeni, Kinyerezi, Jangwani, and Pugu sub-catchments — were identified. The Kisarawe sub-basin upstream has the largest prospective location (covering an area of around 89.89 km^2) since it has a less populated and developed area, which would allow for enough room to construct a dam while protecting the downstream from frequent flooding. According to the capacity and other requirements of the receiving stream downstream, the chosen dam locations could hold approximately 75.15% of the runoff produced in the catchment before releasing it at a controlled rate. The outcomes of the study demonstrate further the effectiveness of geographic information systems in determining the characteristics of dam sites and in designing sustainable dams that take land surface cover into account.
Keywords: site characterization, geographical information system, dam sustainability, land use land cover, engineering design, urbanization.

1. Introduction

Dams are huge hydraulic structures that date back thousands of years and are still used today to provide water for irrigation, industry, and home use. Moreover, dams are well-known as a means of storing water for hydroelectric power generation and river traffic. The type of land surface cover, however, can have a big impact on dam sites. Changes in the land surface cover have a significant likelihood of impacting evapotranspiration rates and surface runoff, and they may also have an impact on infiltration and stream discharge. To be more precise, land cover influences how quickly a sand dam reaches its storage capacity as well as how quickly that storage is used up [1]. Therefore, if a dam location site has been poorly selected, it can have several negative effects, including the risk of erosion leading to mudslides and landslides, the potential for receiving either high or low flows that were not anticipated during the design process (potential failure), as well as be linked to significant negative economic benefits. Consequently, one of the most important steps in creating sustainable dams is to consider the spatial distribution of reservoirs while choosing the placement of the dam.

Development activities alter the land cover in urbanizing catchments, turning it mostly into impermeable surfaces like tarmac roads, pavements, rooftops, and so on. More stormwater runs on the surface and moves quickly toward a neighboring stream as a result of the increase in impervious surfaces than it would if it were to move underground [2-3]. This situation results in so-called flash floods because an enormous amount of stormwater runoff must be absorbed in a stream at once, exceeding the stream's capacity [4]. The primary aim in many research involving surface waters, particularly streams, is flowing channel identification [5]. Depending on the developed flow routes, the direction of the flow and flow discharge can also be calculated. For many years, catchment flow routes have been automatically extracted using the digital elevation model (DEM) [6-7].

DEM is used as an input to extract stream networks and depicts the terrain's 3D geometry [8]. The DEM can be accessed with various resolutions on a number of open-source web forums. DEMs with higher resolution are preferred because they produce more accurate findings [9]. Sinks (depressions) are present in DEM, which signifies that certain locations lack data. To create a continuous drainage network, the sinks can be eliminated by interpolating the values of the neighboring pixels. By using the Fill Sinks tool during the catchment delineation, ArcGIS offers an automated method of filling the sinks [10–12]. In the realm of earth science, drainage networks, along with their channel connections and watersheds, are generally recognized as fundamental ideas. Prior to now, topographic maps and aerial photos were processed manually as part of the catchment delineation procedures. The usage of Geospatial Information Systems (GIS) has largely replaced human labor in the present thanks to technological innovation that makes it possible to employ sophisticated instruments [13-14].

Geography, civil engineering, computer science, land use planning, and environmental science are just a few of the academic and technological sectors that have been involved in the development of GIS into a mature study and application area throughout the years. When it comes to spatial queries that may be utilized to enhance location research, GIS is regarded as being extremely helpful. Moreover, GIS will play a crucial role in the creation and use of future location models [15]. Before deciding where to build a dam and planning it, it is crucial to carry out a site characterization that requires data collecting, field research, and interpretation. The majority of site characterization techniques, however, are both time- and money-consuming and relatively expensive. Therefore one of the interesting ways for the characterization of dam sites can be a combination of various GIS technologies.

This study explores the possible use of a variety of GIS-based techniques for the characterization of dam sites. The Msimbazi watershed in Dar es Salaam, Tanzania, is delineated using GIS-based methodologies for catchment delineation in order to find prospective locations for flood mitigation dams. The US Army Corps of Engineers Geospatial Hydrologic Modeling Extension (HEC-GeoHMS) plugin for ArcGIS was utilized for the study to drain streams in the study basin. Using satellite imagery, the conclusions of the catchment delineation were verified. The Landsat photos were used for the geographic study of the surface land use and land cover. The catchment slope, the number of networks in the sub-basin, and the land surface cover were taken into consideration when choosing a location for a dam.

2. Materials and methods

2.1 Study area description

The Mzimbazi catchment is situated in Dar es Salaam, Tanzania, and is one of the largest in the region. It is located between latitudes 6°27' and 7°15 South of the Equator and between longitudes 39° and 39°33' East of Greenwich. The Msimbazi river flows over the city of Dar es Salaam, originating from the higher portions of the Kisarawe district in the Coastal region, before emptying into the Indian Ocean. As an ungauged catchment, Mzimbazi is frequently affected by floods during the wet season, causing significant damage to low-lying areas. The catchment is subject to land-use changes due to construction activities such as settlements. The basin experiences a tropical climate, with two rainy seasons from November to January and March to May, and an average annual precipitation of 1,150 mm. Daily temperatures range from 17 to 33 ^{0}C.

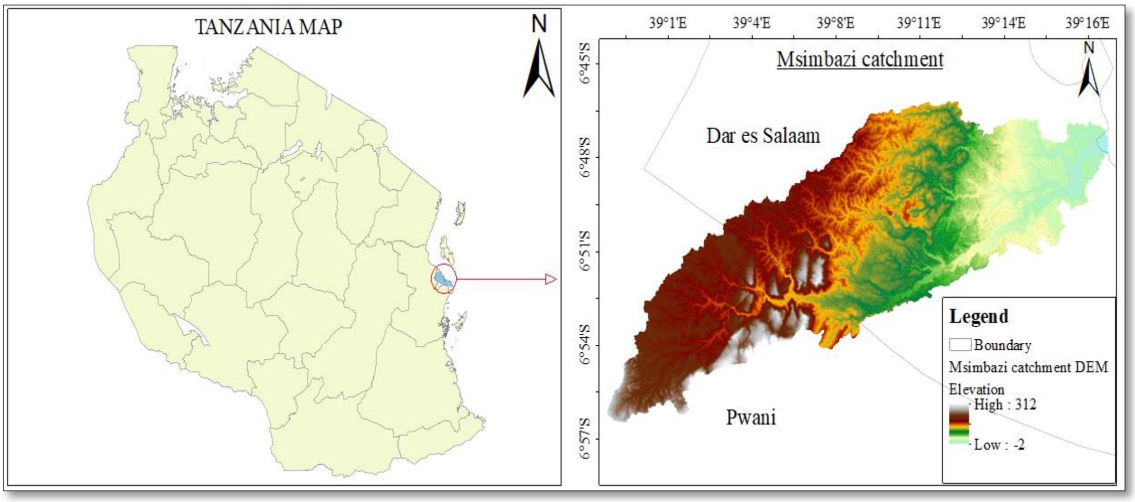

Figure 1 – Study area

2.2 Datasets

To define the catchment, the HEC-GeoHMS plugin for ArcGIS 10.5 was used. After that, the LP DAAC-controlled online open-source database was used to obtain the ASTER GDEM with 30m resolution DEM (NASA Land Processes Distributed Active Archive Center). The watershed's streams and bounds were assessed using Google Earth-based inquiry methodologies while using the stream shapefile of the catchment that was obtained from Google maps for DEM-Reconditioning. The Google Earth Pro desktop version 7.3.2.5776 provided the images with a resolution of 4800 x 2718 (64-bit). For the analysis of land use and land cover, Landsat photos were downloaded from the United States Geological Survey (USGS) website. The estimation of discharge for each sub-catchment and the entire catchment was done using the rational method. The Tanzania Meteorological Agency's (TMA) recording of the 100-year extreme rainfall event that occurred on December 20, 2011, served as an input for estimating runoff flow.

2.3 DEM preprocessing

By extracting the geomorphologic properties of the catchment, ArcGIS 10.5 was used to generate catchment layouts and produce natural flow patterns (drainage routes). The output was then overlaid against a few chosen georeferenced shapefiles in ArcGIS, and the findings were verified. The full process is summarized in Figure 2 below [16].

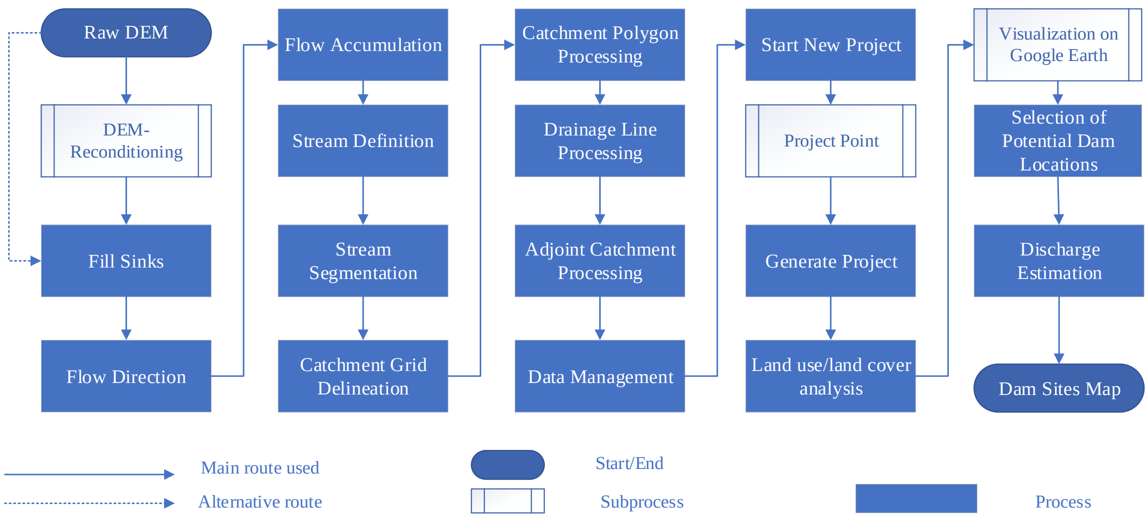

Figure 2 – General study flowchart

The DEM-Reconditioning was the initial stage of the catchment delineation. The area downstream of the Msimbazi catchment is relatively flat, and there are numerous structures (such as bridges) that cross the streams (Figure 3). As a result, the process of developing flow paths may run into difficulties when it reaches these areas [17] and those where the streams are covered by structures because it may be unable to determine the precise path to take. As a result, this study fixed the delineated streams into their precise routes using the DEM-Reconditioning technique and the catchment's accessible streams shape-file. Afterward, sinks in the DEM were filled using the Fill Sinks tool in HEC-GeoHMS tools. This was done to make sure that if cells with higher elevations are located close to cells with lower elevations, the flow of water will be impeded and trapped in the lower-height cells, making it impossible for the water to exit the cells.

The further processes included catchment grid delineation, catchment polygon processing, drainage line processing, adjoint catchment processing, flow direction, flow accumulation, stream definition (where the stream threshold is set), stream segmentation, and stream segmentation. The direction of the sharpest slope, or largest drop, from each cell, determines the flow direction. It is calculated using the formula in Eq (1).

$$\text{Maximum\_drop} = \frac{\text{change\_in\_z–value}}{\text{distance} * 100} \quad (1)$$

2.4 Project development

The design of HEC-GeoHMS incorporates more sophisticated features for the creation of catchment boundaries and streams. Following the DEM preprocessing, the projects for the entire catchment and each of the different sub-basins were created using the Project Setup submenu. A project was started using the Start New Project tool, data was set using the Data Management tool, and a project was generated using the Create Project tool. Runoff and water quality simulation require precise identification of the watershed. However, due to significant depressions and minute elevation changes in local-scale plains (Figure 3), the accuracy of digital elevation models (DEMs) continues to be problematic and may not produce accurate drainage networks [18].

Figure 3 – Real scenarios of catchment delineation challenges

2.5 Land use/ land cover analysis

The examination of land use and land cover helped choose the runoff coefficient. The high-resolution Google Earth photos and the Interactive Supervised Classification technique in ArcGIS were used to assess the land surface cover, which is defined from the existing use of the land, with the aid of having adequate information on the study catchment. The analysis was limited to the primary five land use/land cover classifications (Table 1), and the impervious coefficients were allocated in accordance with the guidelines provided by the National Land Cover Database 2011 Legend [19]. The watershed delineation data and the land use/land cover results were then integrated in order to assess the selected dam sites in terms of the state of land surface cover.

Table 1 – Definition of the land use/land cover classes

Category	Description
Water	Areas of open water that are frequently covered by less than 25% of soil or vegetation.
Low-intensity development	A variety of places are made up of vegetation, built objects, grassland, arable land, and cultivated crops. Surfaces that are impervious make up 20% to 49% of the overall cover.
Medium-intensity development	greenery mixed with artificial materials. Impervious surfaces account for 50% to 79% of the overall cover.
High-intensity development	Areas that have been extensively developed and are home to a significant population. 80% to 100% of the surface is made up of impervious surfaces.
Forest	Generally, more than five meters tall trees dominate areas.

2.6 Dam site selection

Sites for dams were selected based on the catchment slope, land surface cover (as confirmed by satellite photos), and the number of networks in the sub-basin. Also, consideration was given to where to construct dams so that they wouldn't directly obstruct the catchment's primary stream of water flow. The general strategy is designed to keep the mainstream flowing normally throughout the flooding season while the dams either hold back or keep the excess runoff. This strategy is advantageous because it gives the mainstream enough time to manage the remaining runoff volume because enough runoff is captured in the dams during the flooding (high flow) season.

3. Results

As was already mentioned, one of the most important aspects of the study was the catchment delineation procedure, which was made possible in large part by the use of the HEC-GeoHMS software as a plugin for the ArcGIS 10.5 program (Figure 4). Some of the geomorphological datasets that were gathered during the process include the delineation of stream networks, the main catchment boundaries, the demarcation of sub-catchment boundaries, slope profiles, and stream cross-sections. It is also important to note that the HEC-GeoHMS produced sub-basins and streams that were well-drained and easily discernible when choosing the probable dam site locations.

Following the DEM processing, 151 tiny sub-basins with 151 streams were generated. According to the hydro-filled DEM, the elevation of the research catchment ranges from 0 to 312 meters, indicating that it is situated in a low-lying area. The lowest elevation is situated downstream of the watershed when its departure pours water into the Indian Ocean. Additionally, the slope changes gradually throughout the basin. The presence of man-made structures like bridges and flat areas makes it harder to determine flow direction precisely since they change the natural trend of elevation.

The Msimbazi basin's land use/land cover classes were successfully classified using the Interactive Supervised Classification on a few selected Landsat images. The Msimbazi catchment was divided into five land use/land cover categories: water, developed medium intensity, developed low intensity, and vegetation. The land use/land cover analysis revealed that the intensity of development increased downstream and decreased upstream (in the Kisarawe hills), where the watershed starts. The developed, low-intensity scenario predominated upstream of the basin, whereas the developed, high-intensity scenario was more easily apparent downstream.

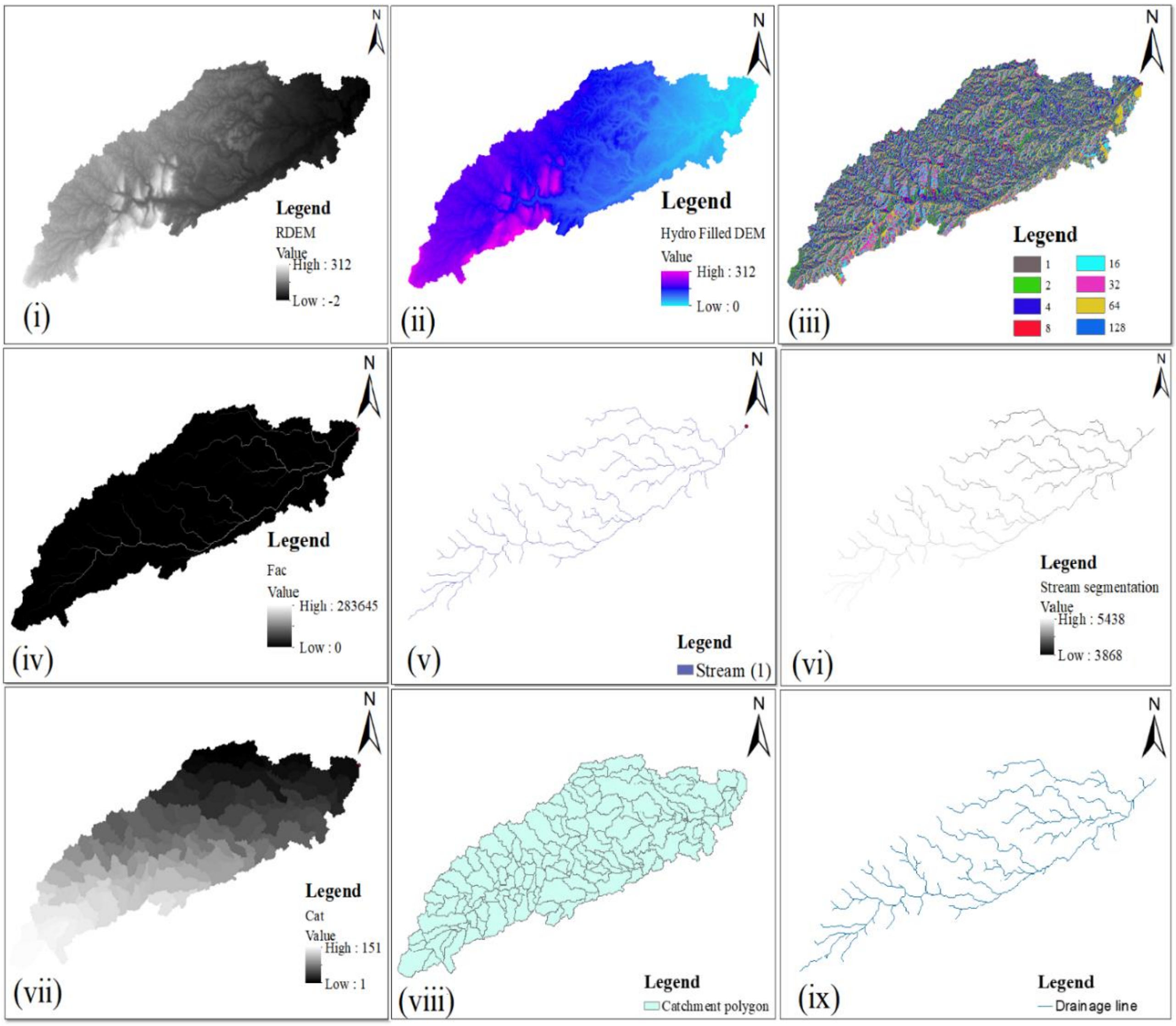

Figure 4 – Steps involved in the catchment delineation (i) input DEM (ii) filling process (iii) flow direction (iv) flow accumulation (v) stream definition (vi) stream segmentation (vii) catchment grid delineation (viii) catchment polygon processing (ix) drainage line processing

After an investigation using a combination of catchment delineation, land use/land cover analysis, and high-resolution Google Earth images, five potential dam site locations were retrieved, including the Kisarawe sub-basin, the Magomeni sub-basin, the Kinyerezi sub-basin, the Jangwani sub-basin, and the Pugu sub-basin (Figures 5, Figure 6 and 7). The streams that contain a substantial number of substreams before emptying into the main channel are where the dam sites' exits are typically found. The site with the highest promise is upstream in the 89.89 km^2 Kisarawe sub-basin; it is less populous and less developed than other potential sites, allowing for the construction of a dam and safeguarding the downstream from recurrent flooding.

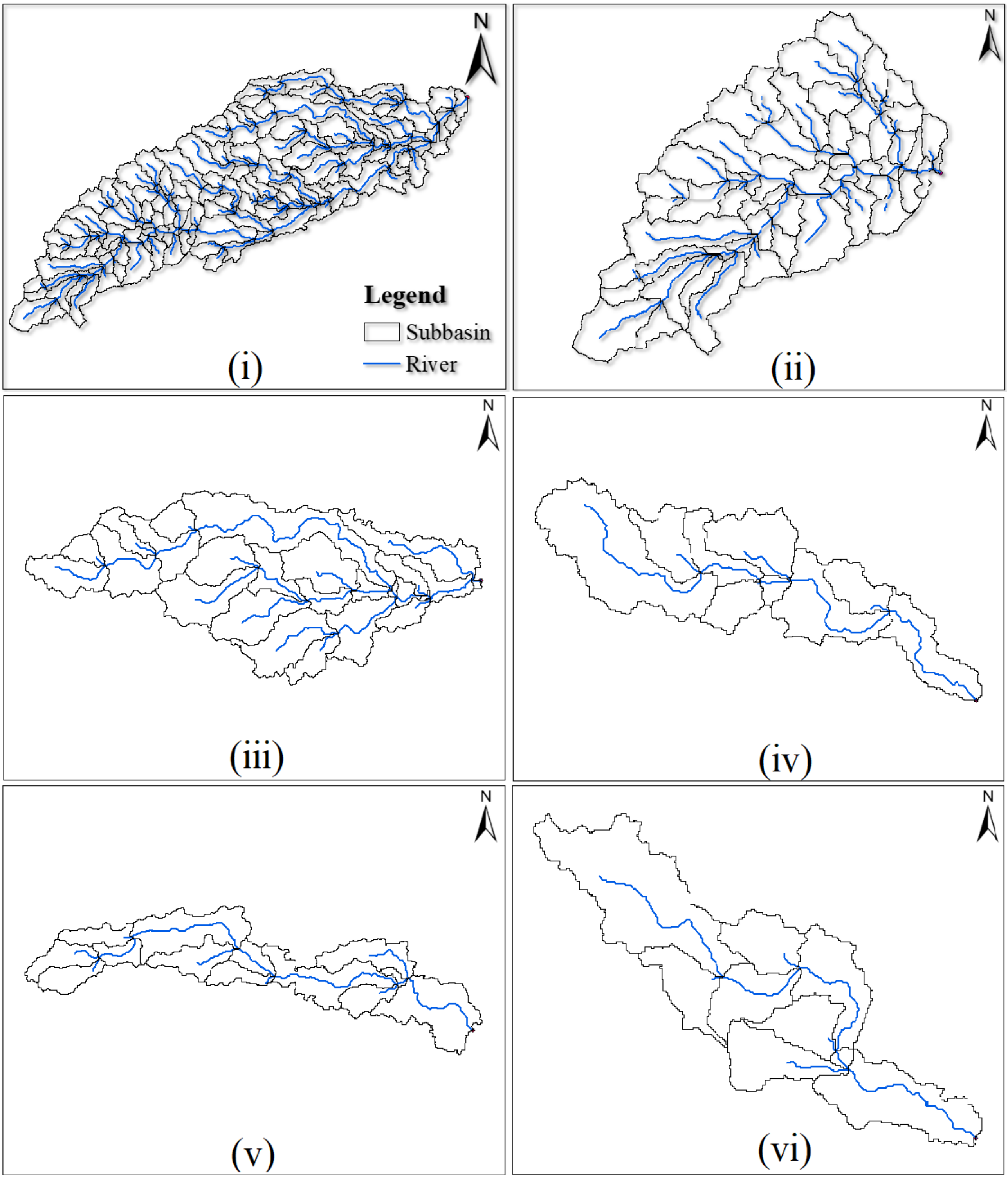

Figure 5 – Delineated subbasins for the selected dam sites (i) number 5 (ii) number 7 (iii) number 9 (iv) number 11 (v) number 13

A summary of the classified land use/land surface cover for each sub-catchment, together with the delimited sub-catchments, is shown in Figure 6. Each sub-catchment has been given the appropriate land surface cover characteristics, as seen in Figure 6. The design team can benefit greatly from knowing the current status of the land surface cover in a catchment before installing a dam in order to foresee potential problems caused by changes in the land surface cover that could influence the operability of the dam. It is crucial to stress that changes in land cover continue to have an impact on weather and climate on a local to a global scale by changing how energy, and water move between the land and the atmosphere.

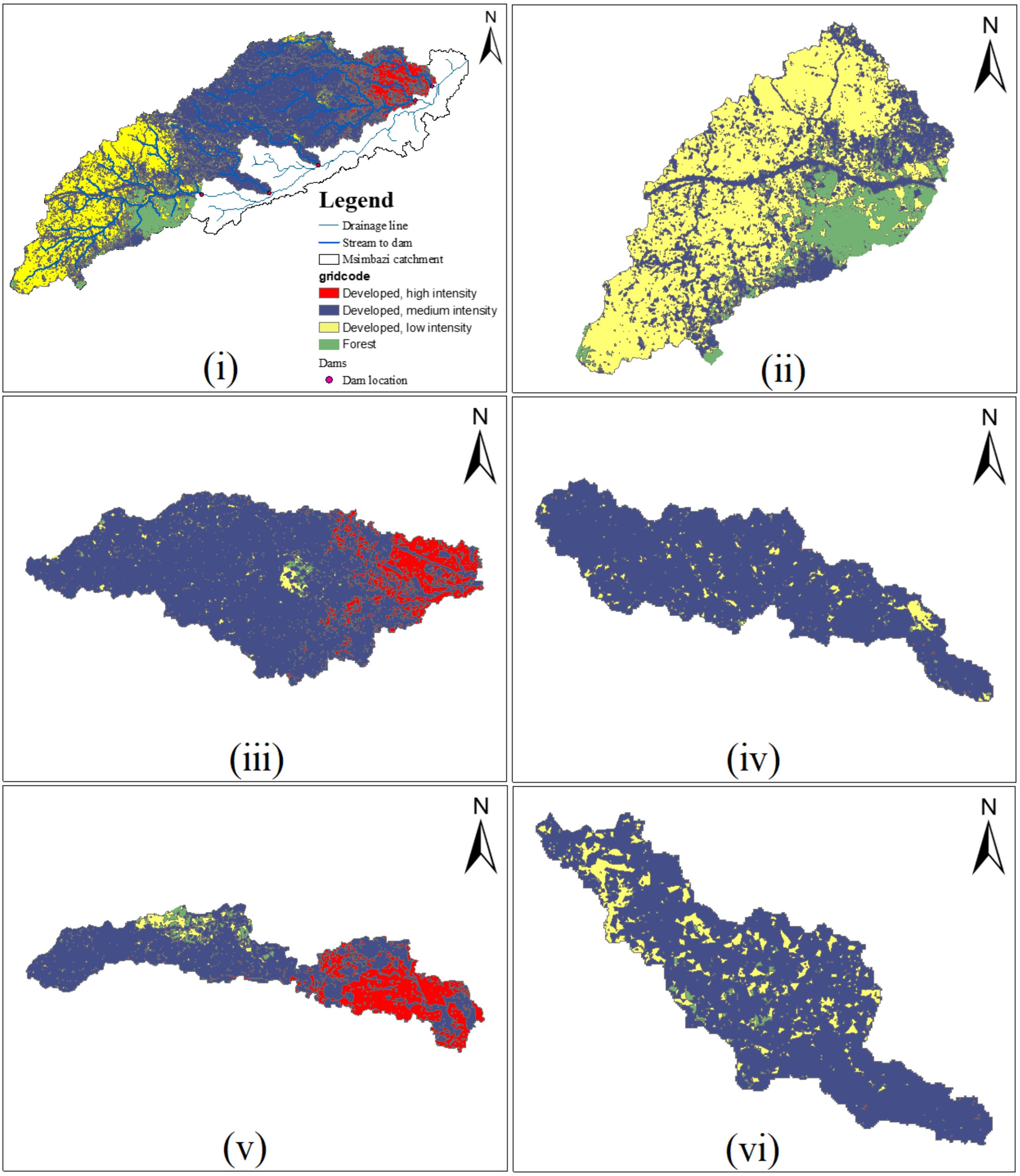

Figure 6 – Distribution of land use and land cover for each subbasin of the chosen sites (i) entire catchment (ii) Kisarawe sub-basin (iii) Magomeni subbasin (iv) Kinyerezi subbasin (v) Jangwani sub-basin (vi) Pugu sub-basin

Figure 7 summarizes the position of the chosen possible dam site as determined by HEC-Geo HMS. Additionally, clearly defined streams that contribute to each chosen dam site can be seen. It should be emphasized that rivers are the result of water moving through gravity from one elevation to another. When rain falls on land, it either soaks into the soil or turns into a runoff, which travels to the sea by flowing downhill into rivers and lakes. The land is not completely flat in most landscapes; it slopes in one or more directions. Small creeks are how flowing water initially makes its way downhill. Small creeks join to become larger streams and rivers as they move downward.

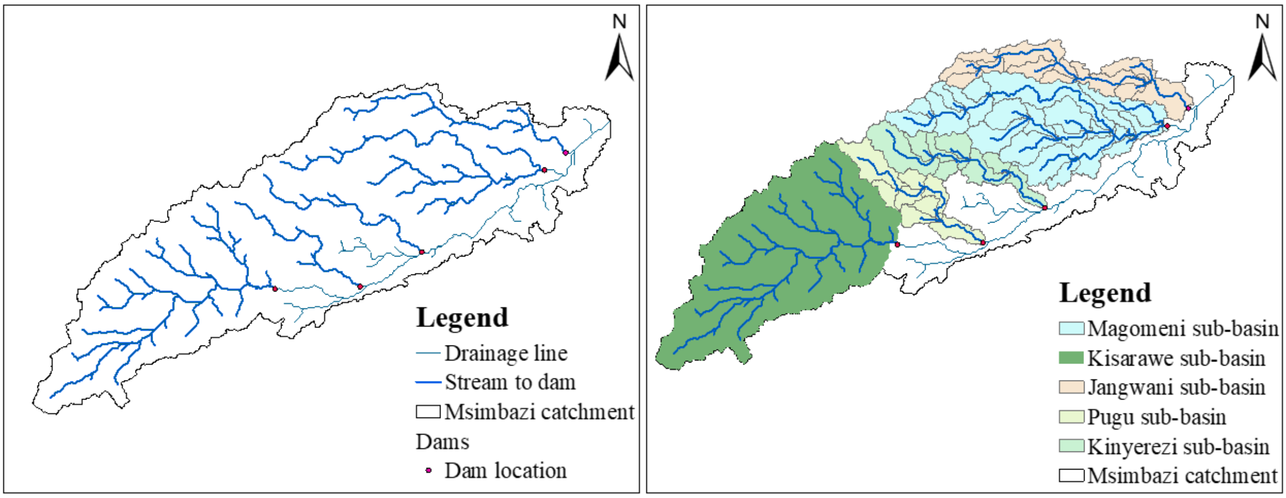

Figure 7 – Dam site locations: Streams only (left), streams with coverage (right)

4. Discussion

The study's conclusions suggest a promising strategy for locating suitable dam locations inside catchments: combining DEM and HEC-GeoHMS methodologies. Remote Sensing (RS) and Geographical Information Systems (GIS) are frequently very useful in providing geospatial data for the evaluation of potential dam sites [20–23]. Additionally, having prior knowledge of the subject matter and technical competence are essential since they allow for the connection between theories and the actual situation on the ground, making it easy to identify potential dam sites [24–26]. 151 small sub-basins with 151 streams were produced after the DEM processing. According to the hydro-filled DEM, the elevation of the research catchment ranges from 0 to 312 meters, indicating that it is situated in a low-lying area. According to López-Dóriga and Jiménez [27], due to their low height, subsidence, and present low sediment supply on the one hand, and their high ecological and socioeconomic values on the other, low-lying coastal areas are high-risk sites for sea-level rise. The lowest elevation is situated downstream of the watershed when its departure pours water into the Indian Ocean. Moreover, the slope changes gradually throughout the basin. The presence of man-made structures like bridges and flat areas makes it harder to determine flow direction precisely since they change the natural trend of elevation.

The Msimbazi basin's land use/land cover classes were successfully classified using the Interactive Supervised Classification on a few selected Landsat images. The Msimbazi catchment was divided into five land use/land cover categories: water developed medium intensity, developed low intensity, and vegetation. The land use/land cover analysis revealed that the intensity of development increased downstream and decreased upstream (in the Kisarawe hills), where the watershed starts. The developed, low-intensity scenario predominated upstream of the basin, whereas the developed, high-intensity scenario was more easily apparent downstream. It should be emphasized that changes in the use of land and its cover have an impact on soil erosion, sediment loads, processes of land degradation, and microclimatic resources at the local level. Each of them directly affects how local societies make a living [28].

A combination of catchment delineation, land use/land cover analysis, and high-resolution Google Earth images was used in the investigation to identify five potential dam site locations, including the Kisarawe sub-basin, the Magomeni sub-basin, the Kinyerezi sub-basin, the Jangwani sub-basin, and the Pugu sub-basin. The streams where the dam sites' exits are located are often those with a sizable number of substreams before they empty into the main channel. The most promising option is the upstream Kisarawe sub-basin, which has a size of around 89.89 km^2 and is less populous and less developed than other probable sites. This makes it possible to build a dam there and shield the downstream from regular flooding. It is important to keep in mind that dams are constructed to safely contain huge volumes of water, which are then released for a number of uses, such as agriculture, hydropower, recreation, water supply, flood control, inland navigation, and so forth. The choice of a dam location is necessary for a variety of operations including irrigation, hydropower, recreation, and water supply. Dam locations should be carefully chosen to increase project safety, shorten construction duration, and cut construction costs. As a result, choosing and assessing a variety of viable dam locations early in the construction phase is essential [29].

Considering the studies conducted in some other parts of the world [12-30-31], The geomorphological properties of a catchment can be easily extracted using GIS-based approaches. This study's objective was to include HEC-GeoHMS tools into the assessment process in order to further investigate how beneficial geo-based techniques are for assessing potential dam sites that are situated in catchments that have experienced flooding. During the installation process, the HEC-GeoHMS was sophisticated enough to detect the absence of Arc Hydro tools and then give the user the option of automatically installing Arc Hydro tools compatible with the version of ArcGIS already installed in the working system. Additionally, the Project Setup section of HEC-GeoHMS produced more hopeful results for catchment delineation following the DEM preprocessing, including streams that were more properly delineated. This approach provides a quick and efficient means to extract, map, and understand the catchment features for the goal of selecting suitable dam site locations, making it seem more practical than having to manually locate the necessary Arc Hydro tools. As was already mentioned, choosing the right dam sites is important for assuring project safety, cutting down on building time, and minimizing construction expenses. As a result, choosing and assessing a variety of viable dam locations early in the construction phase is crucial. Moreover, the ability to develop, modify, and manage pertinent thematic layers makes remote sensing and GIS valuable in choosing the location of dams and reservoirs.

5. Conclusions

The potential applicability of geographical information system-based approaches for dam site characterization has been investigated for a case of the Msimbazi catchment in Dar es Salaam, Tanzania. From the results, total area coverage of 267.24 km^2 was delineated. The following can be concluded from the results:

– An essential component of the study was the processing of Landsat and Google Earth images to describe the land surface attributes of the study catchment for runoff-affecting elements as well as identify any potential practical difficulties for precise catchment demarcation.

– Five land use classes – water, high-intensity development areas, medium-intensity development regions, low-intensity development areas, and vegetation cover—were identified in the analysis using the supervised technique.

– Development activity is more intense downstream of the river and less so upstream. The genuine state of the catchment is revealed by this phenomenon.

– According to the capacity and other requirements of the receiving stream downstream, the chosen dam locations could hold approximately 75.15% of the runoff produced in the catchment before releasing it at a controlled rate.

– Dams can be an important engineering tool in the fight against flooding, especially if they are strategically placed and well-made. In addition, dams built in metropolitan areas can be used for recreational activities, the generation of small amounts of energy, the prevention of soil erosion, and the extension of river flow while preserving the ecosystem of sporadic flashy rivers.

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Received: 26.03.2023
Revised: 30.03.2023
Accepted: 30.03.2023
Published: 30.03.2023