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Small-Scale Catchment Delineation in Coastal Area of Bangladesh: A GIS Based Approach

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***Abstract*— Coastal communities confront a lot of challenges including natural hazard, flooding, cyclone, salinity intrusion, drainage congestion etc in the face of climate change. Recently drainage congestion becomes additional burden in the coastal area of Bangladesh. This paper aims to outlines the method of GIS based catchment delineation. ArcGIS 10.2.2 software and Digital Elevation model (DEM) has been used to delineate the catchment boundary. This study concludes that ArcGIS can be effectively used in catchment delineation. But accurate DEM is the precondition for such sort of delineation and field verification should be incorporated in the GIS based approach.**

Keywords—Catchment; Digital Elevation Model; Flow Direction; Pour Points; ArcGIS.

I. INTRODUCTION

Coastal communities confront a lot of challenges including natural hazard, flooding, cyclone, salinity intrusion, drainage congestion etc in the face of climate change. Recently drainage congestion becomes additional burden in the coastal area of Bangladesh. The incessant heavy down pours of the rainy season causes flooding in the region [1, 2]. This water cannot be drained out because of rising sea levels-leaving vast areas water logged. Localized drainage congestions are reported throughout the coastal zone in many studies. Due to siltation and poor maintenance of the drainage channel networks in many parts of the coastal zone, drainage congestion is already a grave problem, and the problem is likely to increase considerably [3, 4]. According to the water expert drainage congestion may become an even more serious threat than higher flood risks in the coastal zone [1, 4]. Water expert also suggests that proper catchment delineation is the precondition for proper drainage management [5].

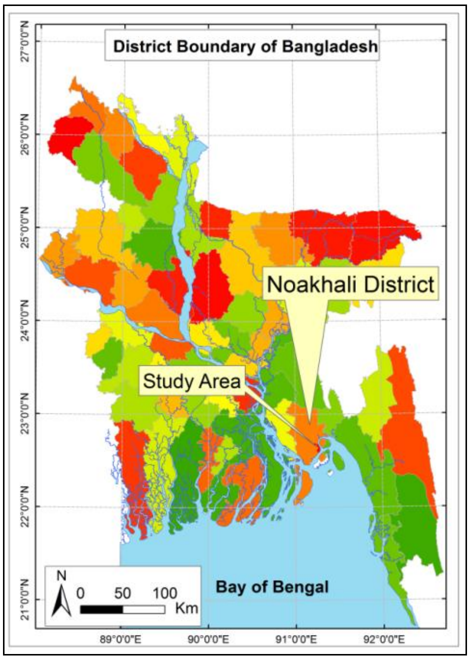
Watershed delineation is one of the most commonly performed activities in hydrologic analyses. Digital elevation models (DEMs) provide good terrain representation from which watersheds can be derived automatically using GIS technology. The techniques for automated watershed delineation have been implemented in various GIS systems and custom applications [6]. This paper aims to outlines the method of GIS based catchment delineation Digital elevation models (DEM).

II. STUDY AREA

A. Location

The study area, Char Maksumul Hakim, under Noakhali District of Coastal area of Bangladesh is located between 22^{0}35'10''N to 22^{0}41'30''N latitude and 91^{0}13'00''E to 91^{0}17'20''E longitude. This area is bordered in the east by the outfall of the Muhuri River and the Chittagong coastline. In the west, the border is formed by the Tetulia River which is on the west of Island of Bhola (Bhola District). In the north, the area follows the coastline of Feni, Noakhali and Lakshmipur Districts. The Chars covers an area of about 3230 hectare. The background story of formation and development of Char Maksumul Hakim occupies hundreds of years' of the hydro-morphological process, as is the case for a lot of chars/islands in the country in the big rivers – Ganges, Padma, Brahmaputra, Jamuna, Meghna and others. The Map-1 shows the location of the study area.

Map1: Location Map of Study Area



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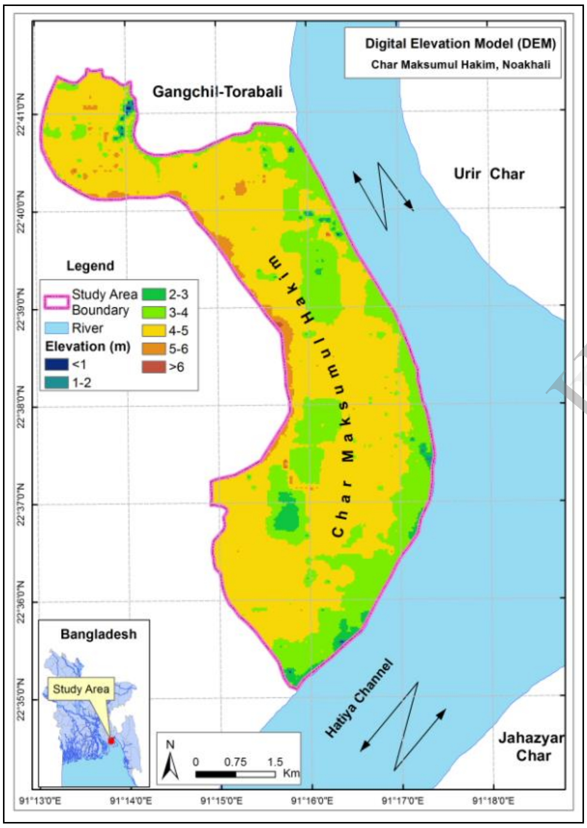
B. Topography

The present land elevation of most of the area (90%) seems to be in the range from about (+) 3.00 m PWD to 5m PWD. The land elevation between 2 m PWD and 5 m PWD cover 35% area of the study area. The embankment on the west and its closest area encompass only around 2% having elevations above 5 m PWD up to 7 m PWD. The chars are submerged by about 1.1 m to 2.7 m deep water (approximately) in the monsoon spring tides, according to preliminary, locally gathered information. Most of the char is used for agriculture (with aman rice as the main crop), though there are a few big fish ponds. The topographic map (Map-2) shows that the eastern part of the project area is lower than western part; in eastern part average land level is about 3.7 m PWD whereas in western part the average land level is about 5.20 m PWD. Average land elevation of the whole project area is about 4.2 m. The Map-2 also shows that some areas in the middle part are characterized with low ditches which are representing the ponds are being used for fish cultivation.

Map 2: Topography of the Study area



C. Rainfall Characteristics

From the past study it was found that only one rainfall station namely Bashurhat of Companiganj Upazila of Noakhali district has the influence in the study area. That study conducted a frequency analysis collecting data for 41 years from 1962 to 2009 of the specific station and found that for an average year (i.e., 2.33 year return period) for 3-days cumulative rainfall is about 315 mm which represents the year 2001; for 10 year return period the rainfall is 443 mm which represents the year 2006 and for 20 year return period the rainfall is 490 mm which represent the year 2002 [7].

D. Drainage System

The drainage pattern of the study area shows that 13 major khals having length of about 36 km have been identified as contributing to the drainage of the study area. The drainage efficiency of these khals has become poor as the khal sections are reduced due to the deposition of sediment over the year during tidal flooding. High tide inundates the area twice in a day bring sediments into the existing khal network which mostly get deposited within the khals and reduce drainage capacity. Delayed drainage in the study area is one of the major constraints for the inhabitants to expected normal activities including agricultural planning and development. It has been observed that high incoming sediment from Meghna River enters into the khal system during the dry period get deposited in front of the existing regulators that were built along eastern boundary dykes.

III. DATA AND SOFTWARE USED

The main data used for the study is the land level of the study area. This data has been collected from secondary source. From this data Digital Elevation Model (DEM) has been created by interpolation method. This is the data for catchment delineation. Inverse distance weighted (IDW) method in GIS environment has been used to interpolate the land elevation data. 30m resolution (cell size) has been used for the DEM. ArcGIS 10.2.2 software has been used for the entire analysis process. Mainly Spatial interpolation tool and Hydrological toolset of ArcGIS has been used in this study.

IV. METHODOLOGY

A. Approach to GIS-based catchment delineation

Numerous algorithms exist for deriving watersheds from digital elevation models. In this study we will use one such algorithm that is built into the Spatial Analyst extension in ArcGIS. GIS based catchment delineation requires to proceed through a series of steps. Some steps are mandatory and some are optional depending on the characteristics of the elevation model (DEM). It is expected that water flow across a surface should always be in the steepest downslope direction in order to have catchment area. That is why once the direction of flow out of each cell is known or identified; it is possible to determine which and how many cells flow into any given cell. This information can be used to define watershed boundaries and stream networks.

Delineating a watershed in ArcGIS requires using a sequence of hydrologic tools that create new output rasters at each step. Generally, the series of tools builds on itself by using the output raster from the previous tool as the input raster for the next tool in the series. The following flowchart[1] shows the process of extracting hydrologic information, such as catchment (watershed) boundaries and stream networks, from a DEM (Figure-1).

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1 http://resources.arcgis.com/en/help/main/10.1/index.html#/Deriving_runoff_characteristics/009z0000005p000000/

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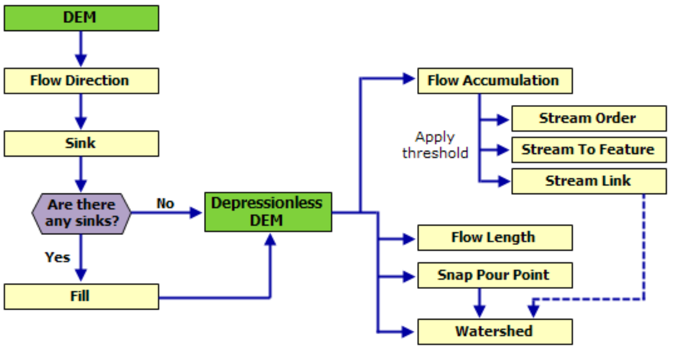

Figure 1: Catchment delineation flowchart

In short, in order to delineate catchment from DEM, we first have to explore the DEM whether there is highest or lowest value referred as peak or sink. If there is any peak or sink it has to be removed and depressionless DEM should be created through fill operation. Then we have to create flow direction from depressionless DEM. The flow accumulation should be created from the flow direction created earlier from depressionless DEM. Then we have to select and snap pour points. And the finally we can delineate catchment boundary from flow direction and snap pour pints. The sequential steps are discussed below.

B. *Exploring the DEM*

A DEM is a raster representation of a continuous surface, usually referencing the surface of the earth. The accuracy of DEM is determined primarily by the resolution. Before using the DEM to be used as the basis of catchment delineation it has to be explored that the DEM is suitable enough to start processing for catchment delineation. In this case it is explored that whether there is any extreme high or low value in the DEM. Such sort of errors in DEMs usually classified as either sinks or peaks.

A sink is an area surrounded by higher elevation values and is also referred to as a depression or pit. This is an area of internal drainage. Some of these may be natural, particularly in glacial areas, although many sinks are imperfections in the DEM. Likewise, a spike, or peak, is an area surrounded by cells of lower value. Errors such as these, especially sinks, should be removed before attempting to derive any surface information. In ArcGIS there is Hydrology Toolset under Spatial Analyst extension. This Hydrology Toolset will be used to delineate the catchment area. Now we will explore the existence of sink in the DEM of study area. To explore the sink we have to create flow direction of the DEM.

C. *Generating Flow direction*

One of the keys to deriving hydrologic characteristics of a surface is the ability to determine the direction of flow from every cell in the raster. The purpose of identifying flow direction is to understand in which direction water will flow from a cell. There are eight valid output directions relating to the eight adjacent cells into which flow could travel. This approach is commonly referred to as an eight-direction (D8) flow model and follows an approach presented in [8]. This direction coding approach is presented by figure-2[2].

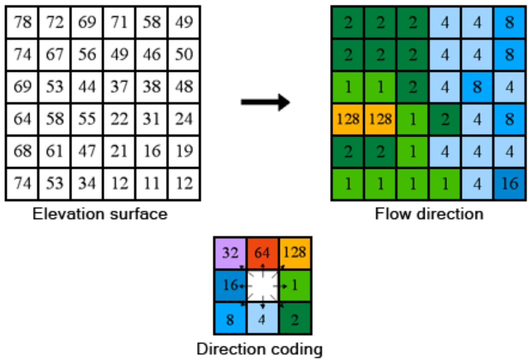

Figure 2: Flow direction coding

The direction of flow is determined by the direction of steepest descent, or maximum drop, from each cell. This is calculated as follows:

*maximum_drop = change_in_z-value / distance * 100*

When a direction of steepest descent is found, the output cell is coded with the value representing that direction. If all neighbors are higher than the processing cell, it will be considered noise, be filled to the lowest value of its neighbors, and have a flow direction toward this cell. Figure-2 shows how flow direction code is determined from the raster. The flow direction code can be easily determined in GIS environment. Thus the "Flow Direction" tool under Hydrology Toolset in ArcGIS has been used to create flow direction dataset from the existing DEM. Map-3 shows the flow direction created from existing DEM. Now we have to examine the presence of sink in the DEM.

2 http://resources.arcgis.com/en/help/main/10.1/index.html#/How_Flow_Direction_works/009z00000063000000/

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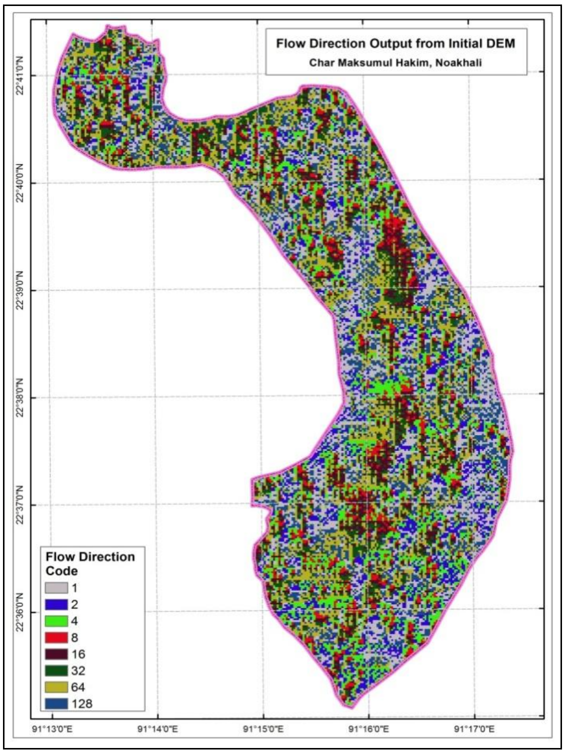
Map 3: Flow direction grid of DEM



D. Identifying Sink

To conduct watershed analyses with a DEM, its surface must be hydrologically connected. In other words, every DEM cell must flow into the next downstream cell until the "water" flows off the edge of the grid. This connectivity within the DEM can be disrupted by "sink". As mentioned earlier a sink is a cell or set of spatially connected cells whose flow direction cannot be assigned one of the eight valid values in a flow direction raster. This can occur when all neighboring cells are higher than the processing cell or when two cells flow into each other, creating a two-cell loop. [3]Figure-3 and figure-4 illustrate the concept of sink and peak.

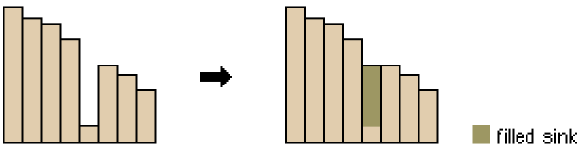


Figure 3: Profile view of a sink before and after running Fill

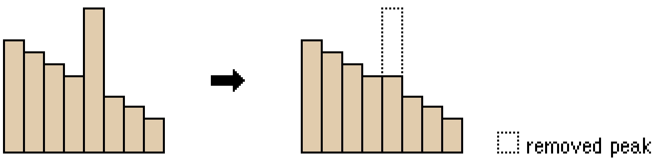
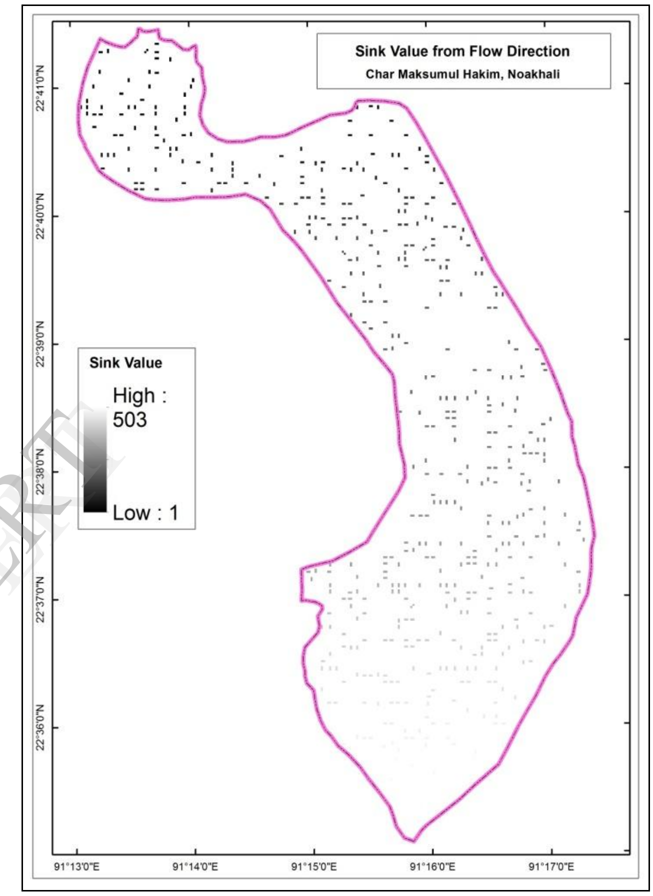


Figure 4: Profile view of a peak before and after running Fill

[3] http://resources.arcgis.com/en/help/main/10.1/index.html#/How_Fill_works/009z00000061000000/

If cells with higher elevation surround a cell, the water is trapped in that cell and cannot flow. The fill sinks function modifies the elevation value to eliminate these problems. Sinks should be filled to ensure proper delineation of basins and streams. If the sinks are not filled, a derived drainage network may be discontinuous [9]. Cells that are sinks can be identified using the Sink tool. Therefore "sink" tool has been used to examine the presence of sink or peak. Map-4 represents the status of sink in the study area created from flow direction raster.

Map 4: Presence of sink in the original DEM

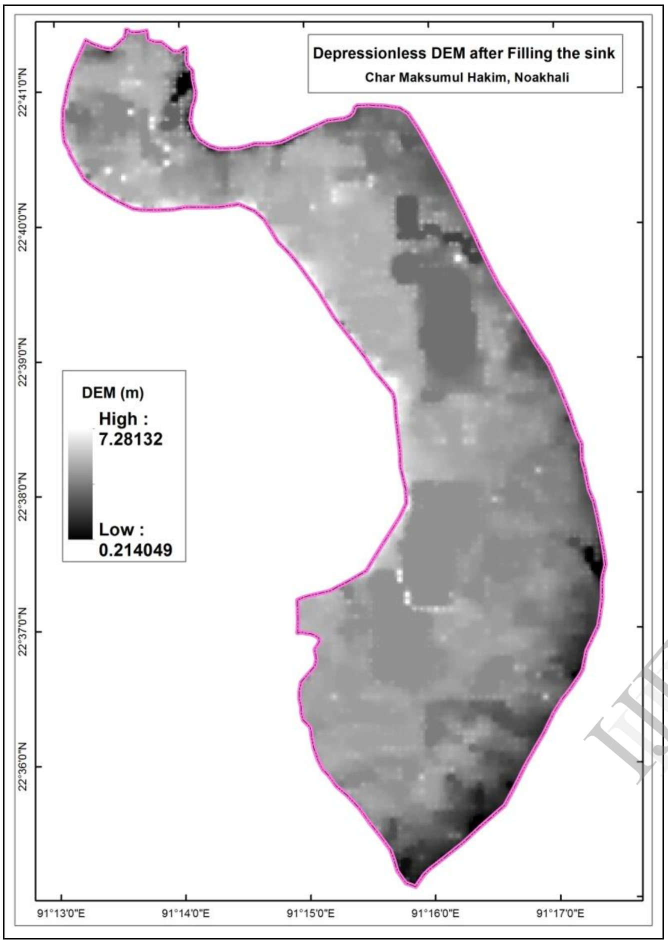


The map-4 illustrates that there exists sink in the DEM. To create an accurate representation of flow direction and, therefore, accumulated flow, it is best to use a dataset that is free of sinks. A digital elevation model (DEM) that has been processed to remove all sinks is called a depressionless DEM. Now we will create depressionless DEM,

E. Creating depressionless DEM

A digital elevation model (DEM) free of sinks—a depressionless DEM—is the desired input to the flow direction process. The presence of sinks may result in an erroneous flow-direction raster [10]. The tools in the Hydrology toolset of the ArcGIS Spatial Analyst extension are useful in preparing a depressionless elevation surface. The Fill tool has been used to create a depressionless DEM. This tool requires an input surface, a fill limit, and an output raster. When a sink is filled, it is filled to its pour point, the minimum elevation along its watershed boundary. Map-5 represents the depressionless DEM. This is the DEM there is no presence of sink. Now this depressionless DEM will be used to create new flow direction in the previous way for further processing. Thus we will get flow direction that can be used to delineate catchment. In the next step we will create flow accumulation.

Map 5: Depressionless DEM after filling the sink



F. Creating Flow Accumulation

Flow accumulation is the next step in hydrologic modeling. Watersheds are defined spatially by the geomorphological property of drainage. In order to generate a drainage network, it is necessary to determine the ultimate flow path of every cell on the landscape grid. Flow accumulation is used to generate a drainage network, based on the direction of flow of each cell. By selecting cells with the greatest accumulated flow, we are able to create a network of high-flow cells. These high-flow cells should lie on stream channels and at valley bottom.

The Flow Accumulation is used to determine how much rain has fallen within a given watershed. This function computes the flows accumulation grid that contains the accumulated number of cells upstream of a cell, for each cell in the input grid. In such a case, the weight raster may be a continuous raster representing average rainfall during a given storm. The output from Flow Accumulation would then represent the amount of rain that would flow through each cell, assuming that all rain became runoff and there was no interception, evapotranspiration, or loss to groundwater. This could also be viewed as the amount of rain that fell on the surface, upslope from each cell.

The results of Flow Accumulation can be used to create a stream network by applying a threshold value to select cells with a high accumulated flow. The Flow Accumulation tool calculates accumulated flow as the accumulated weight of all cells flowing into each downslope cell in the output raster. If no weight raster is provided, a weight of 1 is applied to each cell, and the value of cells in the output raster is the number of cells that flow into each cell [11]. Figure-5[4] represents flow accumulation insights. The top left image shows the direction of travel from each cell and the top right the number of cells that flow into each cell.

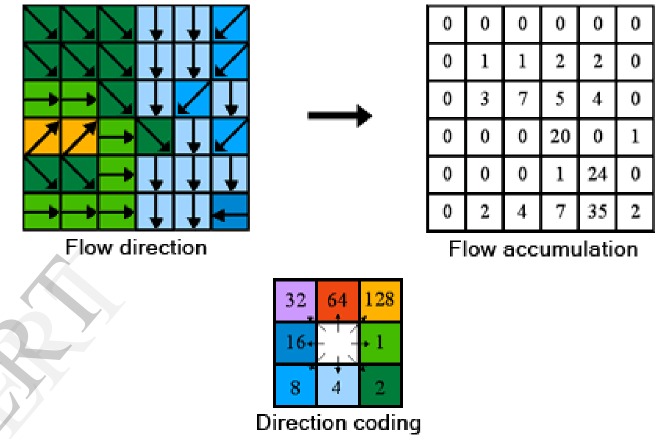
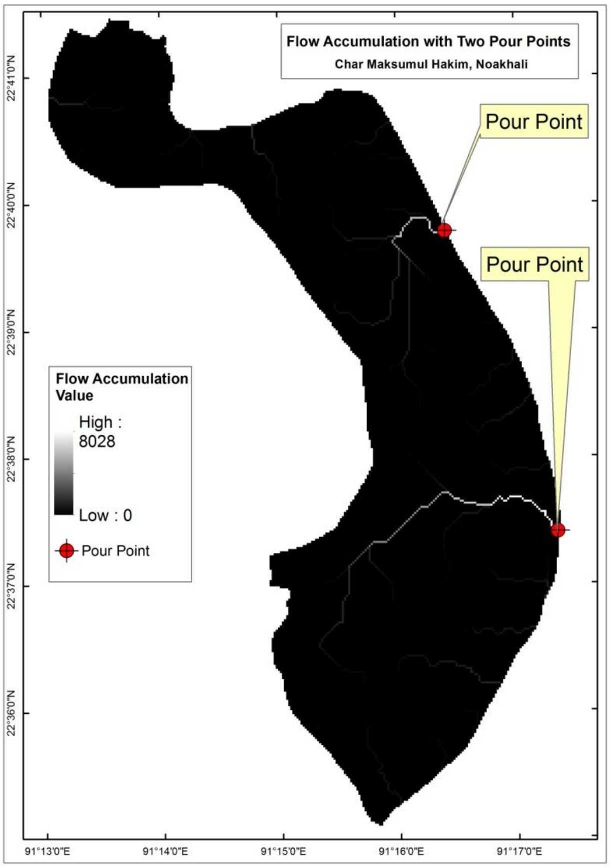


Figure 5: Flow Accumulation direction coding

Thus Flow Accumulation tool has been used to create Flow Accumulation of the study area. In this case the Flow Direction raster has been used as input for this geoprocessing. Map-6 illustrates the Flow Accumulation generated from the Flow Direction raster. From the Flow accumulation raster we can get the indicative drainage channel as represented as white colored cell in the map-6. Now we will delineate the catchment boundary.

[4] http://resources.arcgis.com/en/help/main/10.1/index.html#/How_Flow_Accumulation_works/009z00000062000000/

Map 6: Flow Accumulation with two pour points



G. Snaping Pour Points

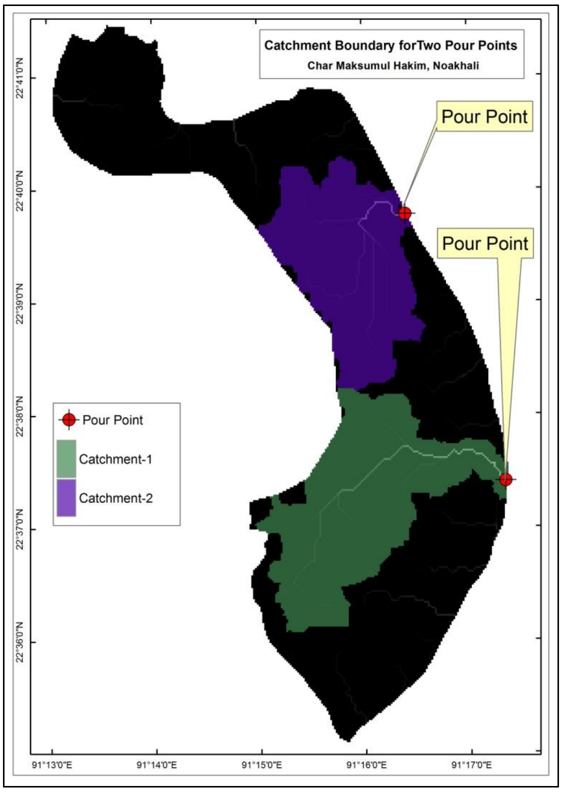
The next step in delineating catchment is to select pour points. These are typically points at the edge of the grid, or just downstream of major confluences. When flow accumulation grid is generated, we are ready to determine the pour point. Considering the general topography of the canyon (or the flow accumulation information), an appropriate location should be determined for the pour point. Pour points are created by adding a new point shapefile. Points should be added that are as close to the center of cells as possible. For this reason, it is good to have the high-flow cells displayed and the data frame displayed at very large scale. Many pour points can be created depending upon requirements. Before watersheds can be delineated, the points need to be converted to a grid layer. The points must have an integer attribute that uniquely identifies each point, because the resultant watersheds will have the same value as the grid cells which act as pour points. That attribute value should be used as the value field in the output grid [12]. Map-6 shows two pour points. Before watersheds can be delineated, the pour points need to be converted to a grid layer. Snap pour point toll has been used to serve the purpose. The Snap Pour Point tool is used to ensure the selection of points of high accumulated flow when delineating drainage basins using the Watershed tool. Snap Pour Point will search within a snap distance around the specified pour points for the cell of highest accumulated flow and move the pour point to that location.

H. Catchment delineation

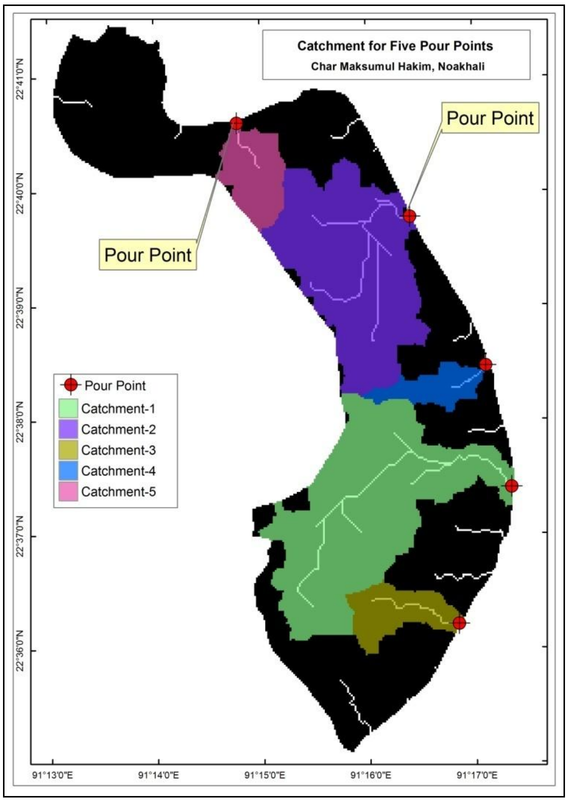
Any location on a landscape can be used to define the upslope area (i.e. watershed) that drains to it. A watershed is defined by this pour-point (its outlet). So it is necessary to choose an appropriate pour point to define the correct watershed. The last step in watershed delineation is to perform the function itself. The grid processor needs three grid layers: pour points, flow accumulation, and flow direction. The watershed tool has been used to create catchment boundary consistent with two pour points. Under watershed tool dialog box, flow direction grid should be specified as the input flow raster, shape file with the pour point or snaped pour point as the feature pour point data. The default setting for pour point field will be ID, but can be any integer field (this value will be assigned to all cells located in the raster). The output from this will be a raster with cells assigned the value from whatever pour point field specified (1 is default) representing the cells inside the catchment, and everywhere outside the catchment is 'nodata'.

The watershed tool determines the contributing area above a set of cells in a raster. The value of each watershed is taken from the value of the source in the input raster or feature pour point data. When the pour point is a raster dataset, the cell values will be used. When the pour point is a point feature dataset, the values will come from the specified field. Thus watershed tool has been used to delineate the catchment boundary. Map-7 represents two catchment boundaries for the area. It can be mentioned that number of catchment area depend of number of pour points. If we use five pour points instead of two then we can get more catchment area as shown in Map-8.

Map 7: Catchment boundary for two pour points



Map 8: Catchment boundary for five pour points



Once satisfied with the delineation, we can now calculate the area of this catchment if needed. There are numerous ways to do this. The raster calculator can be used under map algebra of spatial analyst tool of ArcGIS to calculate the area or this raster can be converted to a polygon feature (e.g. shape file or feature class) and calculate geometry tool can be used in a field to calculate the area within the shapefile's attribute table.

I. *Result and Discussion*

In this study catchment boundary has been delineated for two and five pour points resulting two and five catchment boundaries. This means that number of catchment boundary depends on the number of pour points. The number of pour points selection depends of the topographic characteristics of the area. Map-8 shows the five catchment boundary of the study area. Area of each catchment boundary has been presented in the table-1. From the map-8 and table-1 it is seen that catchment-1 is the largest and catchment-4 is the smallest catchment in size. All catchment covers about 1641.41 hectare of land which is about 50.82% of the total area. It is observed that is much area outside the catchment area as seen in map-8 represented as black sheded area which is about 49.18 % of the total area. Rainfall of this area will not be flown through the designated five catchment areas due to topographic characteristics. So, new catchment area should be delineated to remove drainage congestion of the study area. From the catchment delineation the drainage location can be fixed with internal linkage. Even two or more catchment may be merged with proper drainage work for overall drainage management depending on the topographic characteristics.

TABLE I. CATCHMENT BOUNDARY AREA

Catchment No	Area (Hectare)
1	723.3352
2	589.8259
3	119.4575
4	79.50231
5	129.2826
Total	1641.409

J. *Conclusion*

This study mainly focuses on the methodology of small scale catchment delineation. How this method can also be used for large scale basin delineation also. This study concludes that ArcGIS can be effectively used in catchment delineation. But for this accurate DEM is the precondition for such sort of delineation. This study also concludes that GIS based catchment delineation should also incorporate field verification because there may presence the man mad obstacles like road, embankment and other natural feature. This is why field verification is important for incorporation in the GIS based approach.

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