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Application of DEM to Identify the Infiltration Zones Using GIS

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Abstract: Drainage networks are usually digitized from the existing topographic maps using GIS. Unfortunately, this method is expensive and time consuming. But, nowadays, automatic extraction of drainage network from Digital Elevation Model (DEM) with the help of GIS has become possible and used for hydrological studies. DEM consists of a sampled array of elevations for a number of ground positions at regularly spaced intervals. It is a storehouse of a variety of hydrological information along with terrain characteristics and valuable in groundwater system analysis. In this paper, the contour maps with 20 m vertical intervals were digitized to create DEM data and drainage networks were extracted from DEM. Further, a comparative study of simulated drainage networks extracted from DEM using GIS-based Arc Hydro model is carried out and the drainage digitized from surveyed topographic maps for identifying infiltration zones in an urban watershed, upper Bagmati which covers the whole Kathmandu valley. It has been verified that the automatic drainage extracted technique from DEM is an efficient and cost-effective method in comparison to manual digitization. Hence, thus obtained drainage networks may be very useful for environmental studies, watershed management, and storm water and groundwater system analysis.

Key words: Automatic extraction, groundwater, Kathmandu, GIS, DEM, infiltration zone.

Introduction

The ground water is the major natural resource for drinking purpose. About 50% of the water used in the city of Kathmandu is derived from ground water. The groundwater scenario in upper Bagmati watershed, which receives a substantial amount of annual rainfall, is not very encouraging primarily due to the imbalance between recharge and groundwater exploitation. Due to over extraction, the decline in groundwater levels is continuous and serious. The average discharge rate was 40 litres/second at the beginning of pump operation of production wells at Manohara, Kathmandu, in 1985 but only 20 litres/second in 2000 (Dixit and Upadhya, 2005). On the other hand, urbanization increases impervious surface areas in a watershed and conveys the surface runoff to the storm sewer system which discharges to watercourses. This results in less infiltration and groundwater recharge in built-up areas. Infiltration is a complex process and depends on the conditions of land use, soil type, slope of the surface, evaporation, and precipitation. Therefore, management of drinking water source and protecting its quality is essential to increase efficient use of existing water supplies. Geographic Information System (GIS) and hydrological modelling are closely connected. GIS provides representation of the spatial features of the terrain, while hydrological modelling is concerned with the surface and subsurface flow, its constituents over the land surface and in the subsurface environment. In fact, GIS is an efficient tool for manipulating and storing large volumes of data, integrating spatial and non-spatial information into single system, offering a consistent framework for analyzing the spatial variation, allowing manipulation of geographical information and allowing connection between entities based on geographical proximity (Moore et al., 1991).

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In present study, GIS was used in a number of procedures, including geo-referencing and digitizing for converting hardcopy map information into a digital format to create DEM. DEM is a storehouse of a variety of hydrological information along with terrain characteristics. There are many derivatives of DEM, which are valuable in groundwater system analysis such as slope; aspect; curvature; flow direction and flow accumulation; drainage network and watershed delineation; and stream order etc. In recent years, automatic extraction of drainage network from DEM with the help of GIS has become possible and is now being practised the world over for hydrological studies (Saraf et al., 2004). Hydrological models have been developed to simulate and help us to understand hydrologic processes. With the evolution of GIS, DEM has been used to delineate drainage networks and watershed boundaries to study stream flow hydraulics, prediction of flooding, and modelling of chemical transportation and deposition of pollutants in surface waterways (Moore et al, 1991). Recent studies have demonstrated that the accuracy of parameters extracted from DEM is comparable to those obtained by manual methods while the processing time is much less (Wang and Yin, 1998; Saraf et al., 2004). Two major factors can affect the accuracy of stream networks derived from DEM: the scale of DEM and the drainage density. Wang and Yin (1998) compared the parameters derived from the 1:250,000 DEM with those from the 1:24,000 DEMs in 20 basins ranging from 150 to 1000 km^2 and showed that the goodness-of-fit between parameters estimates based on the DEM varies. Results clearly showed that superior estimations are produced from the 1:24,000 DEMs (Rumman et al., 2005).

Different researchers studied to identify potential infiltration areas using different type of GIS-based hydrological models (Sullivan et al., 1996; Saraf et al., 2004; Rumman et al., 2005). In this paper, GIS-based Arc Hydro model has been used to obtain drainage networks from DEM and investigated the applicability of the drainage comparative analysis approach to identify the infiltration zones in a typical urban watershed, upper Bagmati watershed, Kathmandu. The basis of such identification of infiltration zone is that the water which is coming through rainfall is not completely flowing as surface runoff; rather some loss of water to subsurface through infiltration and hence mismatch between two drainage networks are depicted. But, it is assumed that there is no loss to water when it flows in ground in GIS-based surface hydrological modelling used in this study to extract drainage networks from DEM. Further, it is verified combining with various type of spatial data layer such as landuse, geological information, soil type and topography.

Study Area

The drainage network delineated from DEM and its comparison with the surveyed drainage network has been studied in Bagmati watershed. The Bagmati watershed covers an area of 3500 square kilometre and drains out of Nepal across the Indian State Bihar to reach the Ganges. For technical purposes it has been classified into three main areas: the Upper, Middle and the Lower Bagmati watershed areas. The study area to identify infiltration zones has been carried out on the upper Bagmati watershed which covers the whole Kathmandu valley including its source at Shivapuri of catchment area 583 square kilometre as shown in Figure 1. The valley bottom is composed of the small ridges and elevated flat land and low basins drained by Bagmati river and its tributaries. The average altitude is 1350 metres above mean sea level. The surrounding mountains, whose height range 1500 and 3000 metres contain four major passes. Most portion of the land in the central part of this watershed is urbanized. Rapid urban expansion is taking over forest and agricultural land. The urban growth detection was 10.86 square kilometre from 1988 to 1997 (ICIMOD, 2000), which has been further increased since then. This result increases urban storm peak flows due to the increase of impervious surface in this area and also because of a modification in the catchment areas.

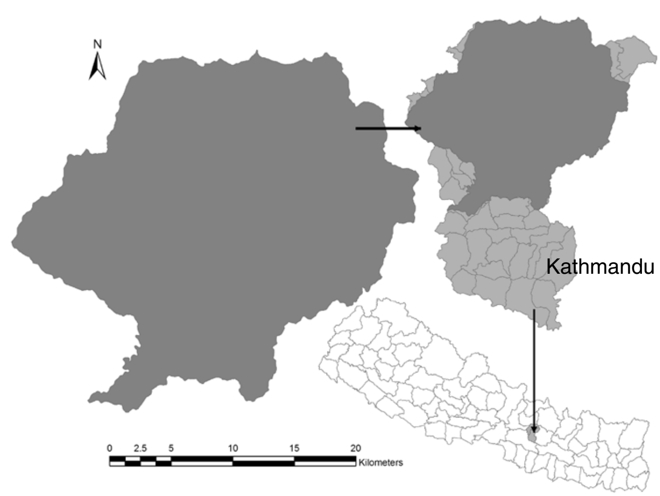


Figure 1: Study area.

Methodology

The flowchart of methodology adopted for identifying infiltration zone is shown in Figure 2. Initially, the hard copy contour maps of 20 m interval with 1:25000 scale were scanned, geo-referenced, digitized and converted to vector data format using GIS technique. DEM data was generated from Triangular Irregular Networks (TIN) data which was obtained from contour map using 3D analyst extension in ArcGIS9 as shown as Figure 3. Thus obtained DEM was of 10 m resolution having 2931 rows and 3313 columns to cover whole study area. The drainage networks were extracted using GIS-based Arc Hydro model from depressionless DEM data for different threshold value. The comparison study between simulated drainage networks from DEM and extracted from surveyed maps was demonstrated and used to identify the infiltration zones. Combining the simulated and extracted stream networks with the geological information maps, soil and landuse map (NGIIP, 1994; Shrestha et al., 1999), the infiltration zone was verified.

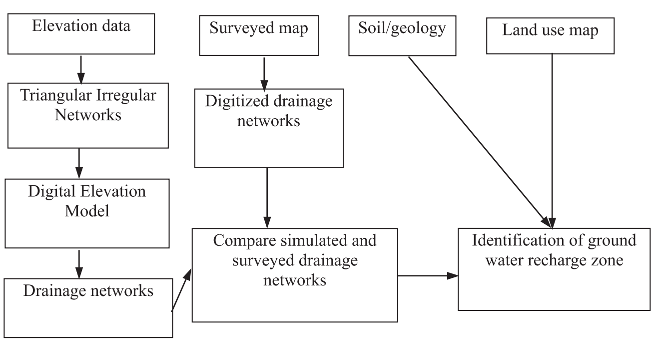


Figure 2: Methodology adopted for identifying groundwater recharge zone.

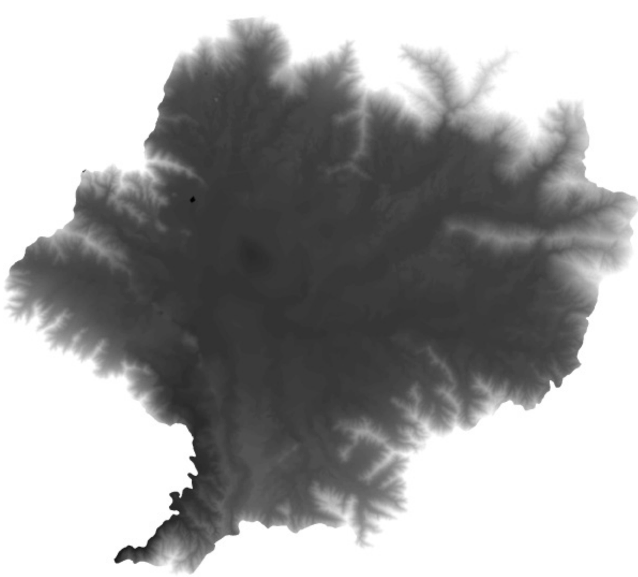


Figure 3: Digital elevation model of study area.

Hydrological Modelling

DEM is a storehouse of a variety of hydrological information along with terrain characteristics. The drainage networks are delineated from DEM which consists of fill sinks, flow direction, flow accumulation, thresholding the flow accumulation, and stream network and stream order as shown in Figure 4. Depression areas surrounded by neighbouring pixels of higher values are always considered as hindrance for the determination of hydrological flow direction using DEM. Some depressions may be data errors while some exist in reality. The approach has been followed in this study to fill depression by raising them to the lowest elevation value on the rim of depression developed by Jenson and Domingue (1988). Several models for defining a grid of flow directions based on a DEM are discussed in the literature. The simplest and most widely used method (often referred to as the D8 method) to define flow directions in DEM is described by Jensen and Domingue (1998). In the D8 model, it is assumed that a water particle in each DEM cell flows towards one and only one of its neighbouring cells that cell being the one in the direction of steepest descent. To assign a flow direction value to a cell, the “distance weighted drop” to each of eight neighbouring cells is computed by taking the difference in elevation values and dividing by $\sqrt{2}$ for a diagonal cell and one for a non-diagonal cell. The flow direction for a cell is assumed to be in the direction with the highest distance weighted drop. In hydrological modelling in ArcGIS, the eight possible flow directions are assigned unique numbers based on the following convention

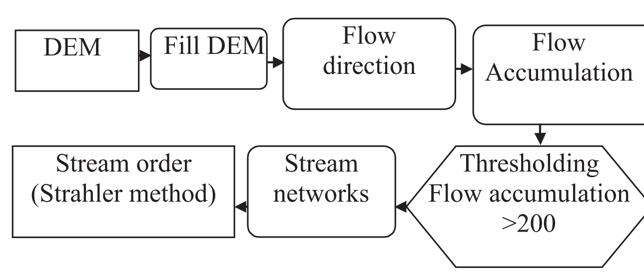
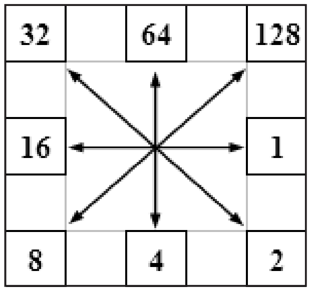


Figure 4: Methodology adopted for derivation of stream networks from DEM using GIS-based hydrological modelling.

shown in Figure 5b. Figure 5a shows an example elevation grid, Figure 5b shows the flow direction assignment convention, Figure 5c shows the numerical values assigned to cells in the flow direction grid and Figure 5d shows the flow directions symbolically with arrows.

80	72	69	71	58	49
75	67	56	49	46	50
70	53	44	37	38	48
65	58	55	22	31	24
68	61	47	21	16	19
75	53	34	12	10	12

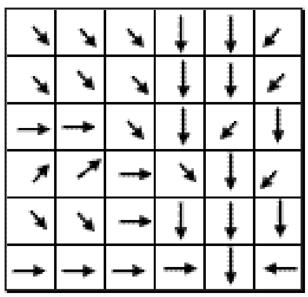
(a)



(b)

2	2	2	4	4	8
2	2	2	4	4	8
1	1	2	4	8	4
128	128	1	2	4	8
2	2	1	4	4	4
1	1	1	1	4	16

(c)



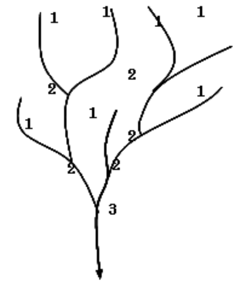
(d)

Figure 5: Flow directions using D8 model: (a) Elevation grid data, (b) flow direction codes, (c) flow direction grid value and (d) flow directions.

Using a flow direction grid and weight grid as input, a flow accumulation function is defined which returns, for each cell, the sum of the weights of all cells that flow to that cell. If the weight grid values are all 1, the cell values in the resulting flow accumulation grid are equal to the total number of cells contributing to that cell. A flow accumulation grid implied by the flow direction grid is shown in Figure 6a. In this case, all weights are assumed to one. The results of flow accumulation can be used to create a raster stream network by applying a threshold value to select cells with a high accumulated flow. The threshold value is the minimum upstream drainage area (threshold area) necessary to maintain a stream. Depending on the choice of threshold value, this method may yield a dense or sparse channel network. The stream ordering has been derived using the drainage networks grid and the flow direction grid. Strahler's stream order method (Strahler, 1957) has been followed in this study. In this method, all links with no tributaries are assigned an order of 1 and are referred to as first-order. When two

0	0	0	0	0	0
0	1	1	2	2	0
0	3	7	5	4	0
0	0	0	20	0	1
0	0	0	1	24	0
0	2	4	7	35	1

(a)



(b)

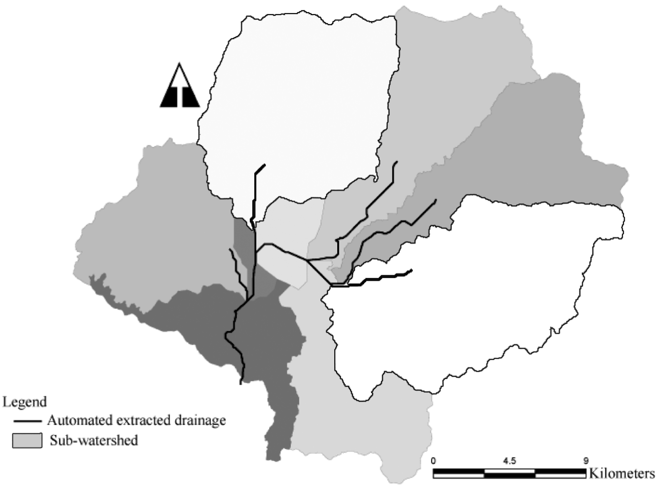
Figure 6: (a) Flow accumulation grid and (b) Strahler stream order.

first-order links intersect, the downslope link is assigned an order of 2. When two second-order links intersect, the downslope link is assigned an order of 3, and so on as shown in Figure 6b. Therefore, the intersection of a first-order and second-order link will remain a second-order link, rather than create a third-order link. Only when two links of the same order intersect the order will increase. Finally, the potential infiltration zones have been identified in given urban watershed based on overlay analysis of surveyed drainage and simulated drainage with the information layers on geology, soil, landuse etc.

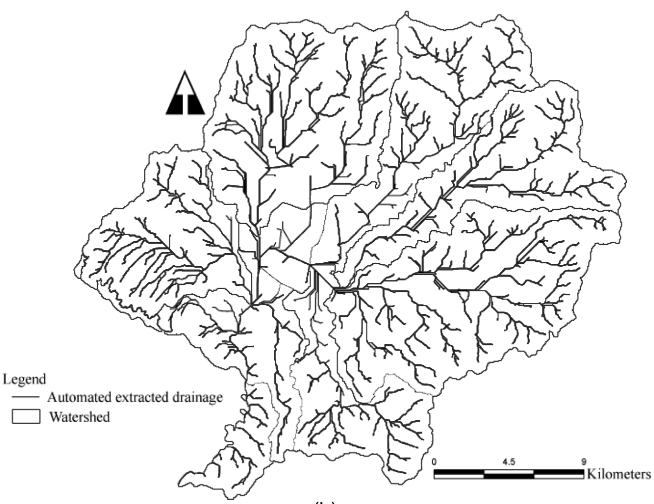
Results and Discussions

By following the various procedures like geo-referencing, digitizing and editing, contour map of 20 m vertical interval was converted into the digital data to feed GIS. Using thus obtained contour map was utilized to create DEM. The drainage networks were extracted using GIS-based Arc Hydro model from depressionless DEM data for different threshold value as shown in Figures 7a, 7b and 7c respectively. The automatic extracted drainage networks were compared and found to be agreeable with surveyed drainage networks shown in Figure 7d and verified that it is more efficient and economic technique. But, the accuracy of network streams delineation from DEM is considerably high because of precise definition of flow directions in high slopes, while in lowlands are poor because of difficulties and fuzziness in definition of flow directions.

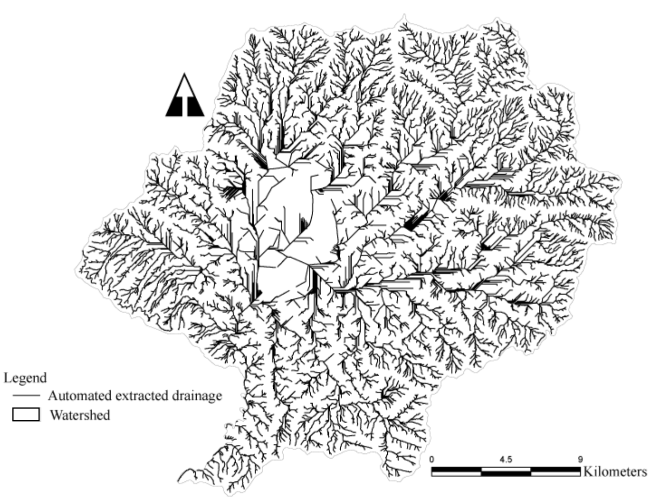
The comparative study between simulated and surveyed drainage network for upper Bagmati watershed shows that there are considerable degrees of match particularly in hilly parts and the area with thick layer of less permeable soil like clayey. Depending on the choice of threshold value, it may yield a dense or sparse drainage network. It was found that the higher threshold value the less dense drainage networks were produced. However, mismatching was found in the core urban built-up area



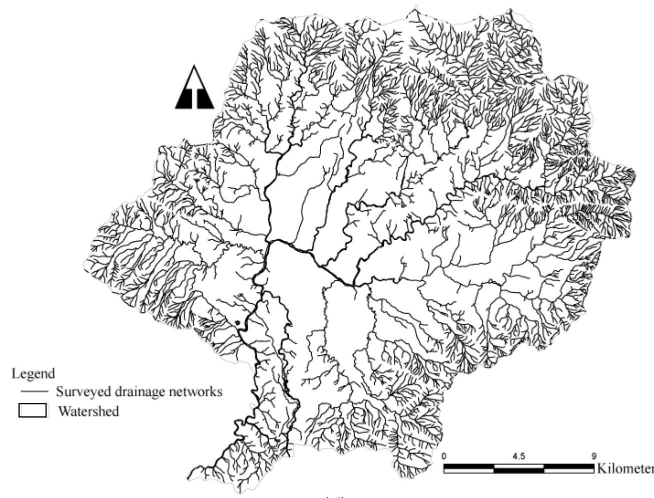
(a)



(b)



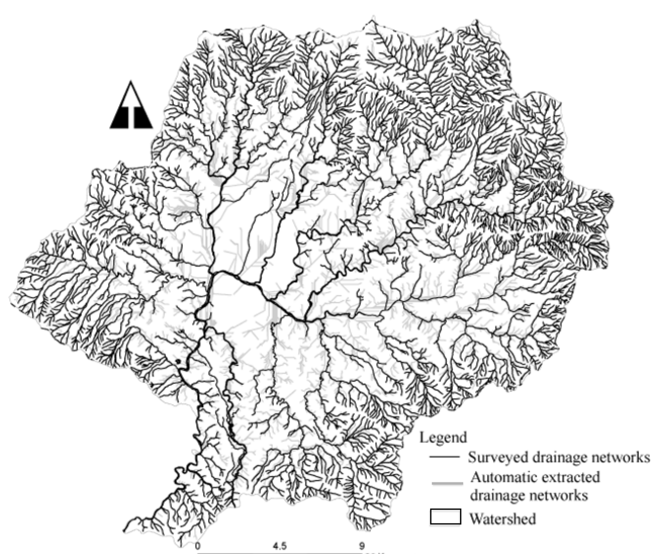
(c)



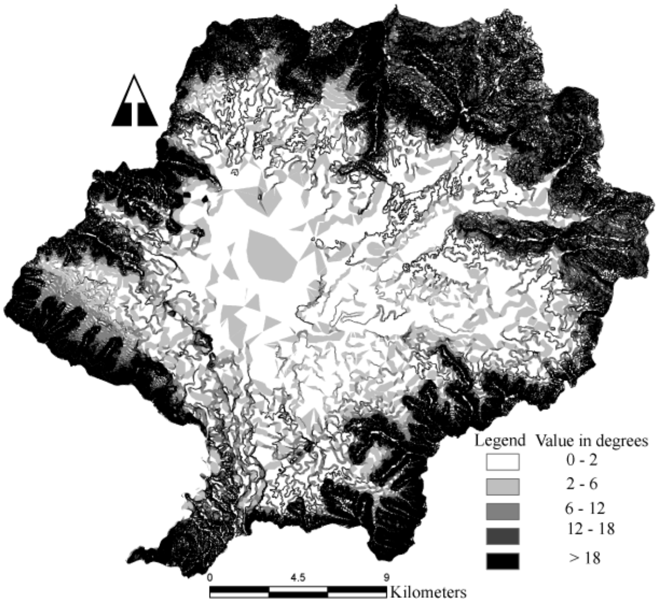
(d)

Figure 7: Automatic extracted drainage networks for different threshold area equal to (a) 28244 pixel out of 564880 pixel, (b) 2825 pixel, (c) 200 pixel and (d) surveyed drainage networks.

as the streamlines are partially enclosed in sewer conduits due to urbanization in these areas as shown in Figure 9. In relatively flat areas where rock and soils are suitable for infiltration, a considerable mismatch has been observed between two drainage networks as shown in Figure 8a. The mismatch between simulated and surveyed drainage networks can be exploited to delineate the infiltration zones as shown in Figure 8b. The areas where filtration is high, the degree of mismatch between simulated and surveyed drainage is high. The basis of such identification of infiltration zone is that the water which is coming through rainfall is not completely flowing as surface runoff; rather some loss of water to



(a)



(b)

Figure 8: (a) Comparison between automated extracted and surveyed drainage networks and (b) Higher degree of mismatch at relatively flat slope.

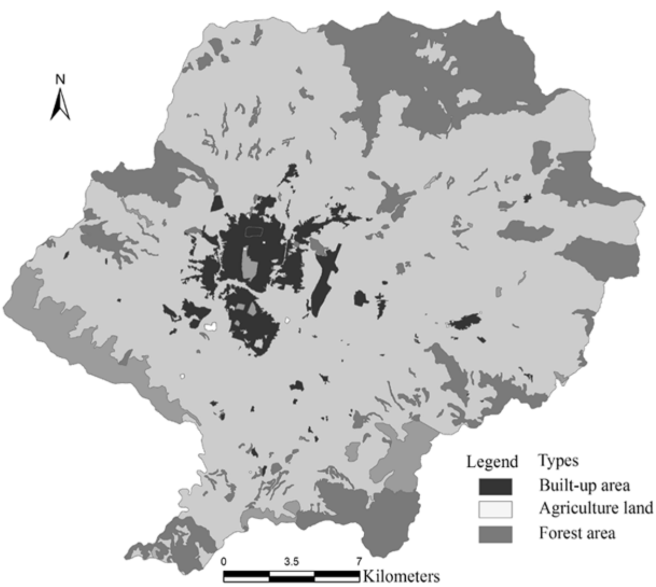


Figure 9: Illustration of mismatching the simulated and surveyed drainage networks in urban areas.

subsurface through infiltration and hence mismatch between two drainage networks are depicted. But, it is assumed that there is no loss to water when it flows in ground in GIS-based surface hydrological modelling used in this study to extract drainage networks from DEM. After overlay analysis of simulated and surveyed drainage networks with information layers on geology, soil and landuse, it is possible to identify the high infiltration areas, where alluvial fan and underlain by relatively permeable silty-sand formation of relatively flat slope with misfit surveyed and simulated drainage network located as shown in Figure 10.

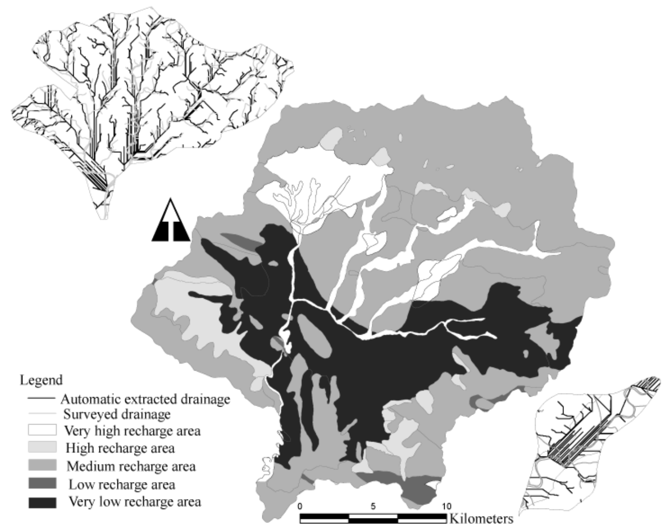


Figure 10: Illustration of groundwater recharge zone after combining the comparative drainage network with geological, soil and existing well information.

Conclusions

A comparative analysis of the drainage network derived from DEM by GIS-based surface hydrological modelling and drainage extracted from surveyed topographical maps has been carried out and found to be agreeable result in given urban watershed. This comparative approach has been used to identify infiltration zones in an urban watershed and considerable mismatch has been observed between two drainage networks. It can be inferred from the misfit that in these areas water is infiltrating more and these may be the recharge areas. Further, it is then verified by combining comparative drainage networks with information layers on geology, soil, faults and landuse, identification of infiltration zone.

However, better information leads to better decisions is as true for GIS as it is for other information systems. It is important to note that mismatch between surveyed drainage with simulated drainage in certain parts of a watershed cannot be attributed due to spatial resolution of the DEM or error in source data and also infiltration loss and evapo-transportation loss are not considered in this method of automated extraction of drainage networks. But, it may be concluded that the misfit between simulated and surveyed drainage networks can be utilized as an indicator of infiltration zones.

Visualizing the distribution of infiltration zones will help us to develop the effective protection strategy for drinking water supply sources in urban watershed. Further, it could be valuable for environmental planners and decision makers to select the area for industry, landfill site etc. such that groundwater contamination can be prevented.

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