Analyzing changes in the surface-subsurface hydrology in the Vavuniya UC limits

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Abstract

Interconnective processes involving surface and sub-surface groundwater reservoirs are complex and need visualization on the spatial domain for developing systems knowledge. In this context, this investigation mainly focuses on analyzing 'how human induced changes to the surface hydrology (i.e., in the overland flow) have impacted on the subsurface hydrology in the Vavuniya UC limits'. Due to the lack of adequate data, field based model building approach and subsequent simulations become essential for developing management scenarios. Using data gathered as such spatial mapping of terrain, geometric network modeling of water flow lines were done in Arc GIS 9.2 based on the info from Google Earth services to get a model for the estimated area of groundwater potential. For validation of the model, the actual state of groundwater's potential was modelled using 190 point (based) data of the depth of water table gathered in-situ. It is seen that the human induced changes that have occurred in the cascade-lines of water flow have reduced the groundwater potential at present. From the data collected, it is also estimated that 17% of the wells are usually dried-out in the dry season (June – Sep) every year in which 7% of the wells have been further drilled to tap more water. For future researches in this regard, incorporation of population and meteorological data will facilitate the development of better models for the integrated (and sustainable) management of surface-subsurface hydrology.

[Key Words: surface-subsurface hydrology, unconfined aquifer, cascade system, network modeling, spatial mapping, scenarios]

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1.0 Introduction

The degree of coupling of surface - sub surface hydrology depends on several factors such as the nature of underlying geology, properties of surface area, surface hydrology (or the pattern of overland flow), meteorological factors[4] etc. Therefore, modeling/mapping of such physical environmental components i.e., terrain, water flow lines/cascade systems etc., are very important for the understanding of systems' functioning to achieve effective (integrated) management of surface-subsurface hydrology.

In the Vavuniya district, which lies in the dry zone of Sri Lanka, the subsurface hydrology i.e. unconfined aquifer[5] is mainly supported (and impacted) by the surface hydrology which is highly controlled by the 'small tank cascade system' that was influenced by the Rajarata civilization. The cascade system which was principally designed for increasing surface water availability also has inherent sub-surface water conservation benefits. In this, the interconnected system of tanks and intermittent wetlands/paddy fields act as sponges and facilitate the temporary/semi-permanent storage devices of water on the Earth's surface thereby enhancing the recharge of the groundwater aquifer.

Rapid and unplanned urbanization in the past 2 to 3 decades which has occurred in the Vavuniya district has partially collapsed the cascading systems that were functioning well before. This has severely affected the availability and dynamics of the (unconfined) groundwater resource. Research in this field has highlighted that the reductions of catchments – wetlands, tank beds (by means of encroachment) due to unplanned urbanization occurred in this region have reduced the recharging capacity of the groundwater reservoir. This had led to severe shortages in the availability of water for human consumption in the Vavuniya Urban Council area. On the other hand, the increasing population size within a small area has resulted on over extraction of water from the unconfined aquifer at many critical points. This condition may pose the formation of a cone of depression in the water table at these points, and cause groundwater erosion/mining – which could lead to fragmentation of the base flow

[4] Rainfall and temperature influences on the fluctuation of water level in the unconfined aquifer.
[5] Dug wells usually extract water from unconfined aquifer.

in the unconfined aquifer; this possibly may force the unconfined aquifer to eventually turn into a perched aquifer.

According to Cooray (1988), there is no continuous body of groundwater with a single water-table in an area such as that of Vavuniya district which has an underlying geology of crystalline rocks, but rather - **separate pockets** of groundwater occur, each with a distinct water table.

In this investigation, the researchers **aim** to findout the influence of changes in the runoff regimes of the lands surface (as per the influence of the cascade system of tanks) on the (unconfined) ground water dynamics. For this purpose, a sub-set of the cascade system in the Vavuniya Urban Council limits was selected to arrive at a model for describing the dynamics of the influences/s of the cascade system on the (unconfined) groundwater aquifer. As such, the steps taken in this investigation are,

1. Developing a topographic DEM to describe the nature of terrain.
2. Collecting 150-200 field based data points and ancillary data to comprehend actual state of system
3. Developing a GIS based model-profile of tentative unconfined ground water resource profile
4. Qualitative and quantitative identification of areas where the human induced changes have exerted negative impacts on groundwater hydrology.

As this investigation seeks to enquire a causal relationship between the physical environments – i.e. the natural small tank cascading systems and urban groundwater levels (through a spatial simulation analysis), it aims to identify the locations that may face water scarcity in near future and to find out the areas suitable for recharge in order to formulate proper management solutions to enhance the groundwater potentials. This may be useful to the water resource managers in the management of the (unconfined) groundwater aquifer in-parallel to the sustainable management of the surface waters.

2.0 Study area

Vavuniya is situated in the Northern low lands of Sri Lanka, and climatologically - it falls within the dry zone. It lies in between grographical coordinates longitudes 80^0 28' – 80^0 32' and latitudes 8^0 43' - 8^0 48'. Due its strategic geographic location, Vavuniya receives rainfall in a bi-modal pattern, i.e., the rainfall of the district is from early October to late January is the *Maha* season and from late April to late May is the *Yala* season. Geo-morphologically, it is a flat plain having undulated topography with broad valleys and small rock ridges (Samarakoon, 2004) forming cascade based agriculture.

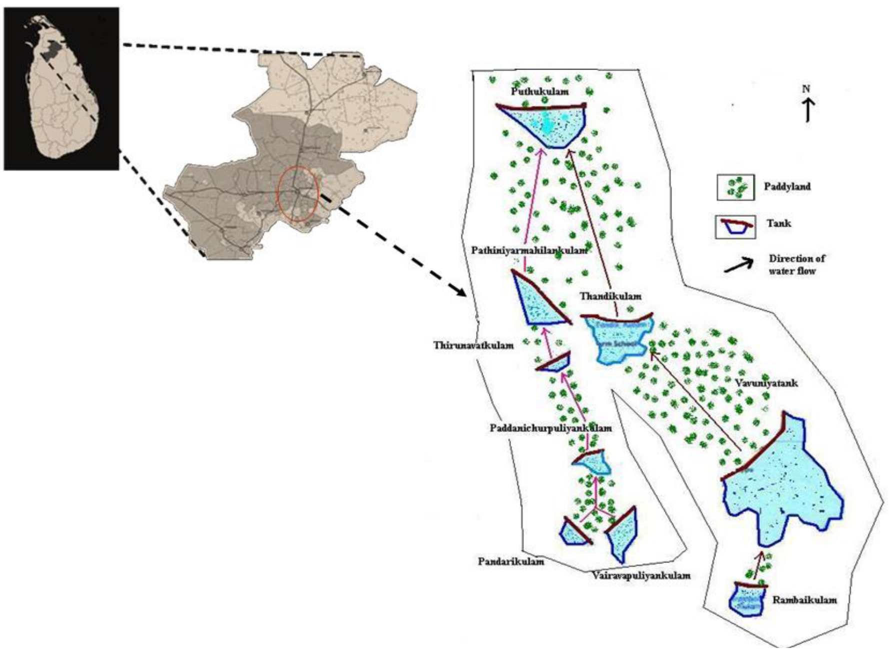


Figure 1: Study area

3.0 Methodology (with materials used)

The methodologies include the modeling of terrain, pattern of overland flow (i.e., cascade system) and the mapping of (unconfined) groundwater potential.

Firstly, a **surface Digital Elevation Model**[6] (DEM) for the analysis of surface properties of the study area was developed using Arc GIS

[6] DEM is the data files that contain the elevation of the terrain to describe the spatial distribution of it above a reference plane

9.2 to get an idea on the pattern of natural drainage/cascading system. Further, **contour lines**[7] were developed and overlaid onto this surface model, so as to trace out best route of water flow (while considering the abrupt/gentle steepness) more clearly to model the cascade system.

A **triangulated irregular network data model** (TIN) was developed to represent abrupt changes of topography in 3 Dimension.

By considering the outputs – i.e. the interpolated raster map, contour lines, and, TIN model; the possible best routes of which the runoff water flows were identified. For this purpose, 725 point elevation data were selected in varying distances (approximately 0m, 100m, 500m, 1000m, and 1500m) from the main axis of selected cascade.

Secondly, development of **geometric network model**[8] in order to model the (cascade system) routes of water flow over the terrain in Arc GIS 9.2. In which, the edges become network links that are representing the stream lines and the nodes become tanks. These are stored as attribute information in the vector database. By setting this model through the incorporation of functioning/malfunctioning junction flags[9], and, edge flags, various analytical operations were performed onto this, to build a final network model to extract/trace the connected and disconnected routes. This was used to identify more recharging zones on the terrain based on functioning of cascade lines. The model outputs obtained at the end of first and second steps were coupled together to assess the trend of groundwater potential of the region.

Thirdly, the **profile of the (unconfined) ground water** was modeled in Arc GIS 9.2 platform using primary data gathered in field. Primary data about 190 points were collected in the field was corrected against the topographic elevation to make the groundwater level dataset above a reference line.

[7] contour lines are lines through all contiguous points with equal height (or other) values (ESRI help file)
[8] is a set of interconnected linear features through which materials, goods are transported in which connected edges and junctions, along with connectivity rules that are used to represent and model the behavior of a common network infrastructure in the real world (ESRI Desktop Help).
[9] The disturbed node (adopted from Oxford Dictionary)

This was corrected using the equation given below.

$$\mathbf{G_A = G_M - (E_T - E_{Min})}$$

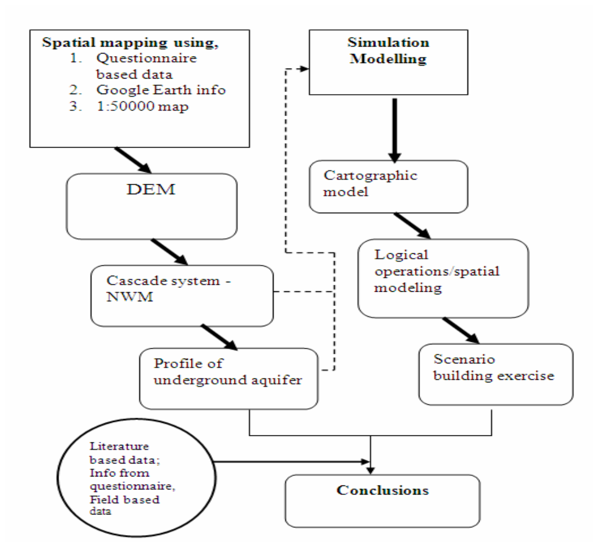
Where, G_A – Depth of actual groundwater, G_M - Depth Measured groundwater[10] , E_T - Topographic elevation of the selected point, and, E_{Min} - Minimum elevation of the collected topographic dataset.

The aim of this model is to assess the co-relation between the cascading system, over-extraction points, so as to identify the hazard/vulnerable areas.

Then the area that has been affected by human induced changes were quantified as calculating the gap between 'expected' and 'observed' groundwater potential of the area.

$$\text{The area affected by human induced changes} = \text{The area of expected groundwater potential} - \text{The area of observed groundwater potential}$$

Flowchart 1 presents a summary of the methodology used for this investigation.



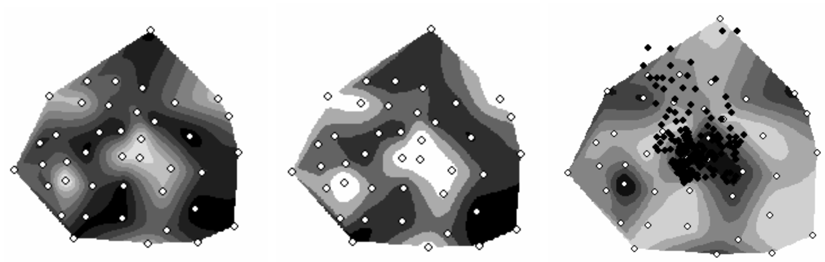
Flowchart 1: Summary of research methodological frame-work

[10] The groundwater level was measured as the distance between ground level and top of the water table.

4.0 Findings

A 'pronounced lack of field data' is a problem faced by watershed and groundwater managers when it comes to modelling issues related to hydrological dynamics in the third world (ACIAR-Partners, 2009). Vavuniya is no exception to this. However, a temporal study by Sivakumar (2007) based on water-level data of dug-wells in various locations in Vavuniya provides some basic ideas onto the conditions of the surface~sub-surface water reservoirs in this district. In Figure 2(a) and Figure 2(b) we present a spatially interpolated comparison of Sivakumar's (2007) findings.

The map of ground water potential illustrated in Figure 2 was developed using data gathered from 42 observational wells by Sivakumar (2007). It indicates that the groundwater potential of this region is not uniform and influenced by some other factor – which could be the nature of surface hydrology i.e., in this context, the presence of cascading system. The data gathered in coarse resolution is not represents the actual state of water potential of this region as 2-3 cascade may lay in between two very adjacent points. So it becomes necessary to collect data in fine resolution to model the connectivity of surface~subsurface hydrology spatially.



(a) **(b)** **(c)**

Figure 2: Coarse resolution (groundwater potential) maps of the whole Vavuniya district (higher potential increases with dark hue) (Data source: Sivakumar, S., 2007) (a) in wet season (May, 2004) (b) in dry season (Sep, 2004) (c) points selected in fine resolution for this investigation.

Therefore, as the corrective and improved measure, in this investigation, a water potential map was developed based on the water level data gathered from 190 points (of the depth of groundwater table) for much smaller spatial unit than that was taken by Sivakumar (2007) in fine resolution to observe the influence of the overland cascade on the under groundwater hydrology (fig 3). The point data were selected in varying distances (approximately 0m, 100m, 500m, 1000m, and 1500m) from the main axis of selected cascade.

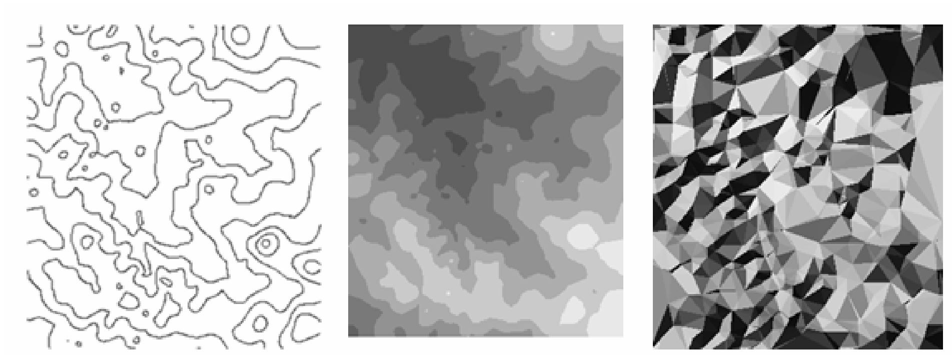

(a) (b) (c)

Figure 3: Various forms of terrain models of the study area (a) contour lines (b) interpolated map (elevation increases with the lighter hues) (c) TIN model of topography

The flow lines of the cascade were drawn onto the terrain map based on the contour gradients (Figure 4).

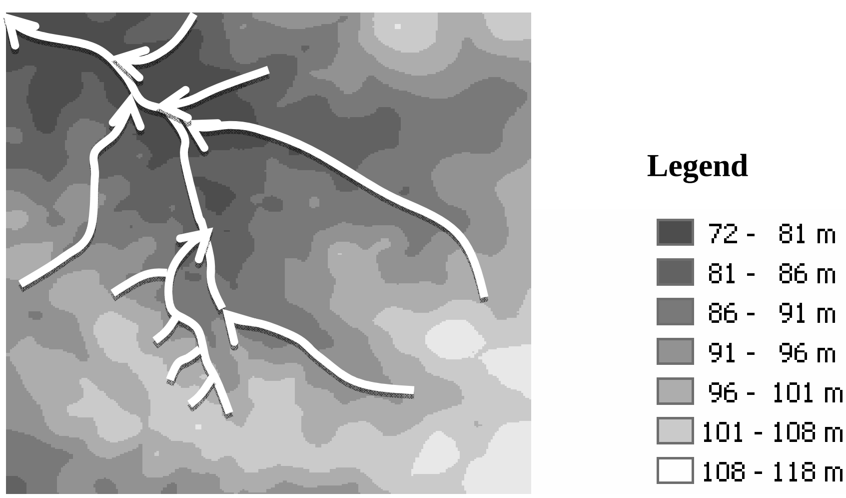


Figure 4: Topography and water flow

As the next step, network analysis was performed on the cascade lines to identify the connected and disconnected paths for assessing the water potential zones as associated surface-subsurface connections (Figure 5).

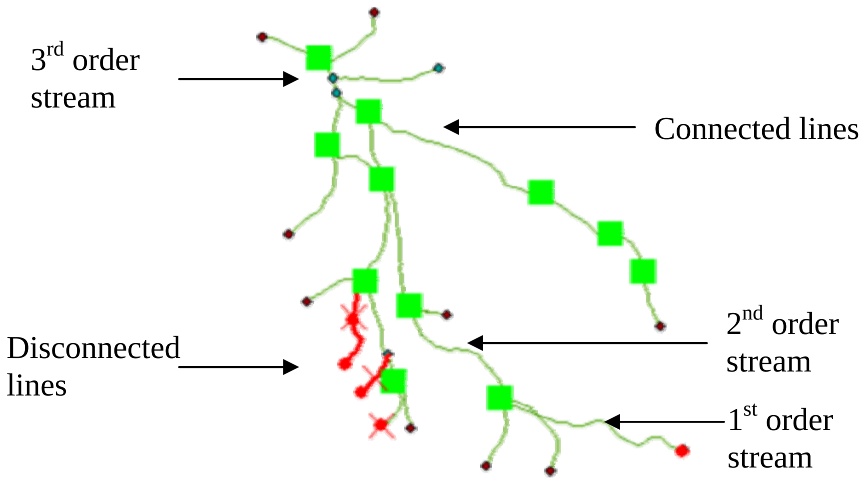
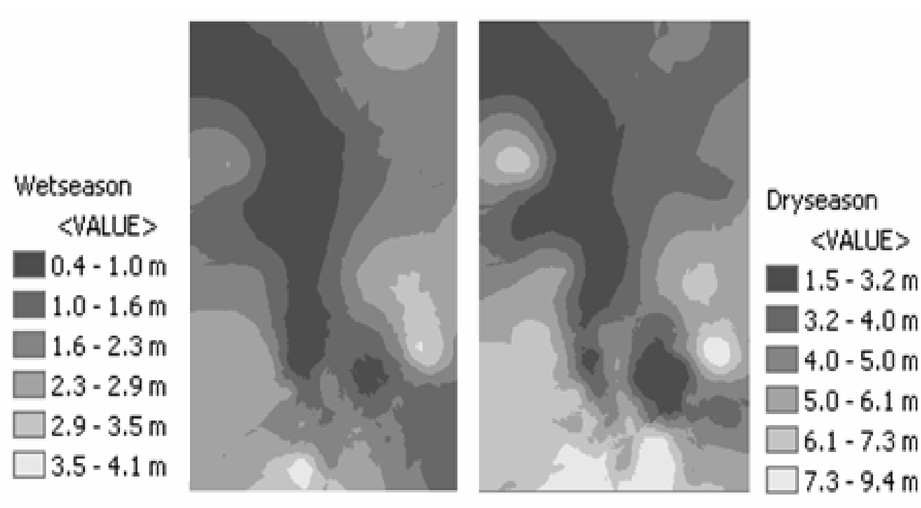


Figure 5: Network diagram of cascade system showing connected and disconnected lines

In order to model the 3D profile of groundwater potential, the 190 data points of the depth of water table gathered using questionnaire were mapped on the spatial domain (Figure 6).



(a) **(b)**

Figure 6: (Unconfined) groundwater potential (a) in wet season (Mar, 2009) (b) dry season (Aug 2008)

The above maps indicate that the groundwater potential of this region is highly influenced with the seasonal changes, i.e., the amount of rainfall received and subsequent increase of water level in cascades are involved in recharging the shallow unconfined aquifer of this region.

5.0 Discussions

Observations gathered during field visit and questionnaire survey are presented in this discussion. Among the data gathered from 190 wells, 17% of the wells are facing severe water shortages in the dry season, in which 7% of the wells have been further drilled to increase their water availability (fig 7). Still, all these wells are facing acute water shortages.

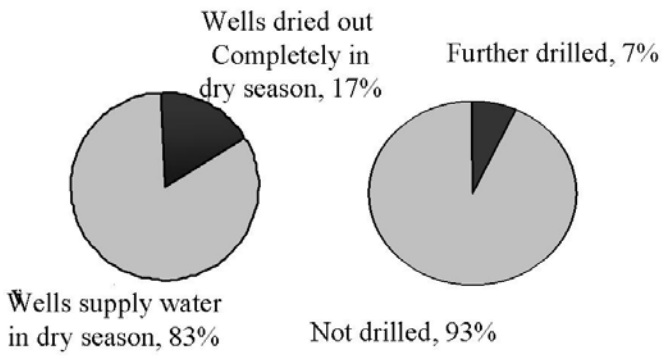


Figure 7: Statistical measures

As Figure 8 shows, the area surrounded by disconnected lines of the cascade has influenced the lowering of the potential of groundwater in that particular locality.

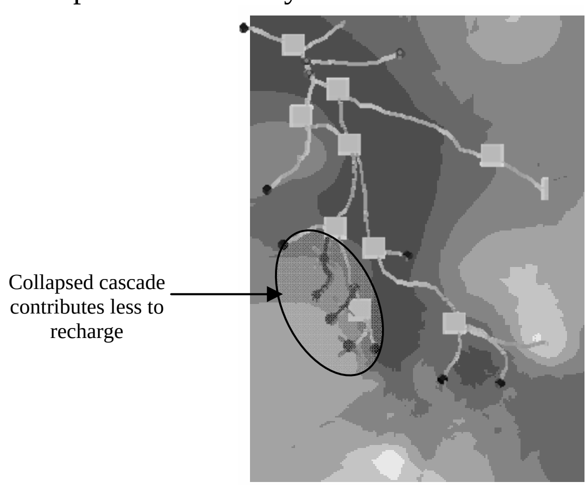
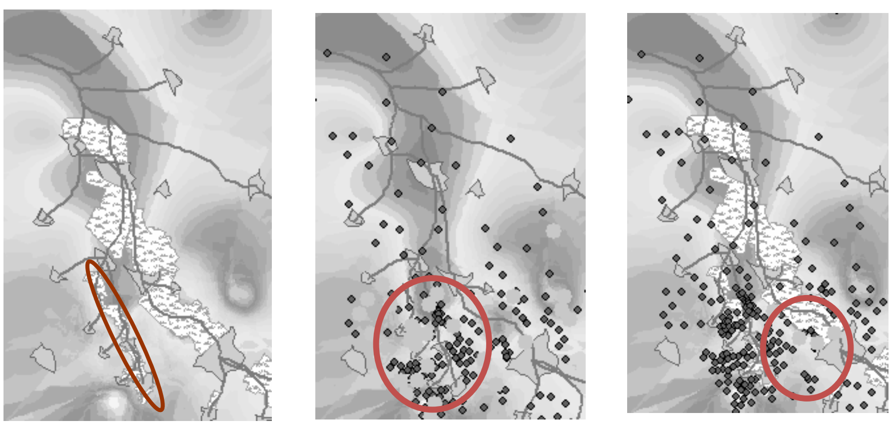


Figure 8: Overlaid map of cascade and groundwater potential

It was observed that the area which faces severe water shortages is very closer to disconnected lines of cascade (Figure 9(b)). On the other hand, reciprocally, areas with higher groundwater potential almost (in both seasons) is observed nearby the sections where the cascade is undisturbed. Yield of dug wells are controlled by the permeability and porosity of the overburden materials (Samarakoon, 2004) i.e., the regolith aquifer. Therefore the undisturbed/well functioning of cascade (i.e., a part of undisturbed regolith aquifer) absorbs more water and providing enough supply in both seasons.

This indicates that the sub-surface hydrology is highly influenced and correlates with the dynamics of the surface hydrology rather than the nature of geology of this region. Further, this also can be supported by using a 'real life' example (fig 9) - that is, the wells selected for the purpose of urban council water supply are located nearby the higher potential region. Figure 9(c)) cements on this argument; i.e., source wells of the National Water Supply and Drainage Board are located very adjacent to the main axis of cascade to ensure uninterrupted water supply.



(a) **(b)** **(c)**

Figure 9: Observation supports research hypothesis (a) Disturbed cascade (b) area where severe water shortage issues are reported (c) the water supply wells located.

Due to the overwhelming lack of geological studies made in this area and the consequent lack of geological literature, the information related to geology and aquifer types was not very much considered in this study. Rather, depending on the map of groundwater potential and the information gathered from questionnaire survey, some ideas about the underground geology were developed and are presented. As the extraction of water from tube wells (from around 35 to 40m) lowers the water table of dug wells located nearby, an argument can be developed that the aquifer-types of this area are confined to semi-unconfined-aquifers.

Finally, to support the argument that: “human habitation and urbanization impacts on the hydrological reserves”, the area of reduced subsurface groundwater potential due to the (urbanizational or) human induced changes that have occurred on the surface hydrology was mapped (Figure 10).

Figure 10: Groundwater potential (a) area of estimated potential (b) area of actual state of potential (c) area of reduced groundwater potential

6.0 Conclusions and Recommendations

According to the findings generated, the unconfined groundwater potential of this region is not uniform throughout the area, it is confined to some particular regions i.e., trapped/pocketed. It is highly influenced by the dynamics of the surface cascading system, where higher water potential is observed in the down stream of the feeder canals. Further, it relies on the degree of stream order in which the area under higher order stream (2nd, 3rd or above) has higher groundwater potential compared to the area under 1st order stream.

The unplanned urbanization activities have affected the groundwater potential of the unconfined aquifer which is now in a state of erosion.

7.0 Suggestions for future research

Future research in these regards should explore the possibilities of the incorporation of rainfall data, infiltration coefficient (based on land cover classes) to further enhance the modelling approach presented that may provide a better model to assess the changes of subsurface hydrology related with other factors (i.e., changes in land cover classes) more accurately. Moreover, inclusion of population data too will be helpful to get an idea on the rate of extraction/exploitation of the aquifers.

In addition to this, quantifying the area those have been affected by human induced changes and developing scenarios for estimating the area which is expected to be affected in near future also will give an index for the formulation of management options at present.

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