Assessment of groundwater vulnerability in Walawe basin, Sri Lanka.

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Abstract: Groundwater vulnerability assessment is a process to identify the susceptible areas for the sustainability of groundwater quality and it has been used as an effective tool for planning, developing, and management of groundwater resources. In the present study, DRASTIC model (Aller et al, 1987) has been used as a feasible methodology to identify areas susceptible for the maintenance of groundwater quality in Walawe river basin, Sri Lanka. The main objective of the study is to use DRASTIC model to assess the potential level of groundwater vulnerability to pollution and to compare the areas with land use activities to represent the degree of usage of fertilizers in agriculture. The Geographical Information Systems (GIS) have been used to develop vulnerability maps, showing the relative vulnerability of the area and maximum potential of vulnerability to ground water pollution with reference to a given maximum DRASTIC index. The ground water vulnerability maps are compared with the agricultural land use pattern of the area, it is noticed that, the areas with intense agricultural activities, overlapped with the high DRASTIC index values. This shows that the extensive usage of fertilizers and pesticide could be the source for highest for the vulnerability. In the area with higher DRASTIC index, more attention should be focused to establish monitoring network for adequate groundwater quality control and to reduce the anthropogenic stress on groundwater resources.

Résumé: L'évaluation de la vulnérabilité des eaux souterraines est un processus d'identification des surfaces susceptibles pour la préservation des eaux_souterraines et elle a été employée comme outil efficace pour la planification, le développement, et la gestion des ressources en eaux souterraines. Dans la présente étude, le modèle DRASTIC a été utilisé comme méthodologie pour identifier les surfaces susceptibles de contenir des eaux souterraines de qualité dans le bassin du fleuve Walawe au Sri Lanka. L'objectif principal de l'étude est d'employer le modèle DRASTIC pour évaluer le degré de la vulnérabilité des eaux souterraines à la pollution et de comparer ces zones avec les activités agricoles pour representer le degré d'utilisation des engrais. Les Systèmes d'Information Géographiques (SIG) ont été employés pour développer des cartes de vulnérabilité, montrant la vulnérabilité relative des zones et la vulnerabilite maximale à la pollution des eaux souterraines determinees a partir d'un index DRASTIC maximum donné. Les cartes de vulnérabilité des eaux souterraines sont comparées au modèle d'utilisation des sols de la zone etudiee. Il est noté que, les secteurs à activités agricoles intenses correspondent à des valeurs élevées de l'index DRASTIC. Ceci demontre que l'utilisation étendue des engrais et des pesticides pourrait être la source de plus haut degré de vulnérabilité. Dans les zones à index DRASTIC, plus d'attention devrait être focalisée afin d'établir le réseau de surveillance pour contrôler la qualité des eaux souterraines d'une manière adéquate et pour réduire les contraintes anthropogéniques sur les ressources en eaux souterraines.

Keywords: aquifers, groundwater contamination, hydrogeology, land use, mapping, pollution

INTRODUCTION

There is a tremendous increase in demand of groundwater utilization for agriculture, industry and domestic use. At the same time, the adverse effects like depletion of resources and degradation of groundwater quality will also enhance. The increasing trend of anthropogenic stresses on groundwater resource has made it vulnerable. Therefore, it is necessary to improve the planning, development, and management of groundwater resources in order to use groundwater safely without threats of depletion and pollution. Because of the known adverse health and economic impacts associated with groundwater contamination, especially in developing countries, the benefits of tools, used to identify and prevent the contamination are becoming more apparent.

To evaluate the groundwater vulnerability, a methodology has been developed by Aller et al, (1987). This method is called DRASTIC, with seven factors which influence the pollution potential level: depth to groundwater, recharge, aquifer media, soil media, topography, impact of the vadose zone and hydraulic conductivity. Groundwater vulnerability is usually expressed on maps. The main purpose of DRASTIC methodology is to create vulnerability maps that will permit to assess the groundwater pollution potential of any hydro-geologic setting systematically with existing information. The ultimate goal of the DRASTIC vulnerability map is a subdivision of an area into several units showing the differential potential for a specified purpose and use. Many authors provided detail reviews of groundwater vulnerability mapping with respect to groundwater contamination using DRASTIC technique; applied and validated the methodology (Evens et al, 1990; Canter, 1990; Kalinski et al., 1994; Rosen, 1994; Vrba and Zaporozec, 1994; Adams and MacDonald, 1995; Rupert, 2001). In this present study, result of vulnerability assessment in Walawe river basin has been portrayed on a map showing various homogeneous areas, which have different levels of vulnerability. The difference between the areas is however arbitrary, because vulnerability maps show only relative vulnerability of certain areas to others.

APPLICATION OF DRASTIC METHODOLOGY

Seven DRASTIC parameters are divided into either ranges or media types. The depth to groundwater table, recharge, topography and hydraulic conductivity have been divided into numerical ranges while the aquifer media, soil media and impact of vadose zone have been divided into media types. Each range or media type has been assigned with a rating, used to assess the groundwater pollution potential of each parameter. The typical ratings range from 1 to 10. The value of 10 would indicate an area of highest groundwater vulnerability whereas the value of 1 would indicate the lowest groundwater vulnerability. Since the ranges and the ratings of the parameters in the study area are deviated from the values assigned by EPA's committee of experts, the typical ranges and rating schemes given in DRASTIC guide manual (Aller et al, 1987) were modified according to the local hydro-geological conditions. Local modifications are based upon the specific regional data in Walawe basin and the modified ranges and ratings have been accommodated to determine the local DRASTIC index.

The overall grade of vulnerability can be written as a numerical value (DRASTIC index). The DRASTIC Index (DI) for each hydro-geologic setting is obtained by summing up the multiple of rating and the relevant weight factor of each parameter as follows:

$$DI = D_W D_R + R_W R_R + A_W A_R + S_W S_R + T_W T_R + I_W I_R + C_W C_R$$

Where subscripts R is the rating for each factor and W is the weighting factor

Study area: Walawe River Basin

The Walawe River basin is located in the southern part of Sri Lanka, between North latitudes 6^0 00' and 6^0 40' and East longitudes 80^0 40' and 81^0 10' (Figure. 1) The catchment area of the basin is 2442 km^2 and it is the major irrigation area in the dry topics of southern Sri Lanka. The whole basin is subdivided into sub basins and three major sub-basins in the downstream of Udawalwe reservoir have been selected for the analysis depending on the availability of hydro-geological data (Figure. 1). The selected part of the basin is located in the dry zone, which has annual rainfall less than 1500 mm and groundwater is extensively used for agriculture and domestic use.

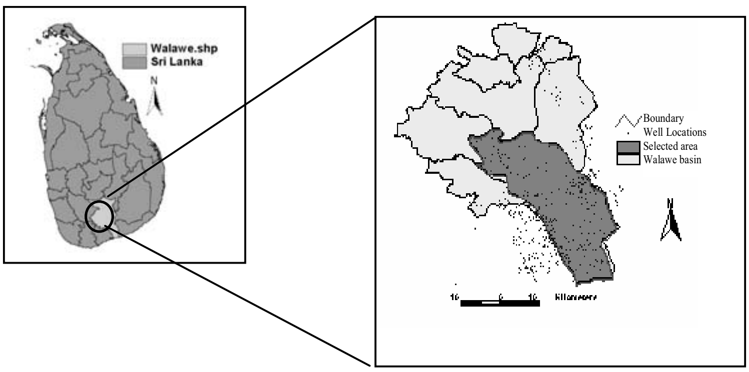

Figure 1. Study area : Walawe River Basin

Groundwater quality in Walawe River basin

The studies have shown very high levels of nitrate in groundwater in some areas in the southern part of Sri Lanka including Walawe River basin (Dissanayake and Chandrajith, 1999). Nitrogen in groundwater in the form of nitrates is a large problem in the area. It is as much as twice the WHO standard of 40 mg/l^{-1} NO^{-3}. Most of this nitrogen comes from agricultural sources. Groundwater contamination by nitrates due to application of fertilizers and livestock waste in agricultural management systems is of wide concern. In Walawe river basin, paddy is the main cultivation and it uses considerable amount of fertilizers as well (Wijayathilake, 2001). In recent years, intensive agricultural practices have increased in response to the population growth, and have resulted very high inputs of artificial fertilizers containing more than 40% (Navarathnarajah, 1994).

Application of DRASTIC model to Walawe River Basin

DRASTIC was implemented with Geographical Information Systems (GIS) environment and it was represented an approach to create vulnerability maps. DRASTIC evaluates pollution potential based on the above seven hydrogeologic settings. Each DRASTIC parameter is divided into either ranges or media types, which have an impact on pollution potential. The depth to groundwater table, recharge, topography and hydraulic conductivity have been divided into numerical ranges and the aquifer media, soil media and impact of vadose zone have been divided into media types. Each range or media type has been assigned a rating, used to assess the groundwater pollution potential of each parameter. The typical ratings range from 1-10 and a value of 10 would indicate an area of highest groundwater vulnerability and a value of 1 would indicate the lowest groundwater vulnerability. Since the ranges and the medias of the most of parameters in the study area are deviated from the values assigned by EPA's committee of experts, the typical ranges and rating schemes given in DRASTIC guide manual (Aller et al, 1987) were modified according to the local hydrogeological conditions, to get a better outcome. Local modifications based upon specific regional data in Walawe basin has been accommodated to corresponding local DRASTIC ranges and ratings.

Depth to water is important, primarily because it determines the depth of material through which a contaminant must travel before reaching the aquifer, and it may helps to determine the contact time with the surrounding media. The ranges in depth to water as defined in the DRASTIC system have been determined based on depths where the potential for groundwater pollution significantly changes. The groundwater level monitoring data recorded in IWMI groundwater database was used to estimate the average depth to the groundwater table. The depth to the groundwater table varies seasonally throughout the year. The groundwater table rises during the rainy period in October – February and it lowers in the dry season. Hence average value of the observed groundwater levels in each monitoring well during the monitoring period was considered to define the ranges for the depth to groundwater (Table 1).

Precipitation is the primary source of groundwater, which infiltrates through the surface of the ground and percolates to the groundwater table. Net recharge represents the amount of water per unit area of land, which penetrates the ground surface and reaches the water table. This recharge water is thus available to transport a contaminant vertically to the water table and horizontally within the aquifer. The net recharge is defined as the total quantity of water, which enters through the ground surface and infiltrates to reach the aquifer. Net recharge includes the average annual amount of infiltration and does not take into consideration the distribution, intensity or duration of recharge events. The study area was divided into seven irrigation blocks based on available meteorological observation stations and average annual groundwater recharge for each block was estimated separately using a simple water balance approach as follows.

$$GR = P + I - O - ET - \Delta SM$$

Where P is precipitation, I is surface water inflow to the irrigation block and O refers to the surface runoff at the outlet of the irrigation block. ET is evapotranspiration and ΔSM means storage of soil moisture. GR is the groundwater recharge

Since the study area is located in the dry zone with average annual rainfall of less than 1500 mm, the recharge values are less than the ranges given in DRASTIC scheme (Aller et al, 1987). The ranges for the parameter ‘recharge’ has been modified according to the local ranges and assigned with respective ratings (Table 1).

Aquifer media refers to the consolidated or unconsolidated rock, which serves as an aquifer. Aquifer media has been designated by descriptive names according to the available aquifer media in the study area. The data related to the aquifer media was obtained from the literature and collected data of the geology exploration reports. The aquifer types available in the Walawe basin were classified into seven groups. The ratings were assigned based on the DRASTIC manual for the available aquifer properties (Table 2).

In DRASTIC, soil is defined as the upper weathered zone of the earth, which averages a depth of six feet or less from the ground surface. Soil has a significant impact on the amount of recharge which can infiltrate into the ground and hence on the ability of a contaminant to move vertically into the vadose zone. The presence of fine-textured materials such as silts and clays can decrease relative soil permeability and restrict contaminant migration. With reference to the soil maps of the area (Geological Survey and Mines Bureau, Sri Lanka), the soil types were classified into groups. According to the DRASTIC rating scheme with reference to US Soil Conversation Service, suitable values were assigned to each soil group (Table 2).

As used here, topography refers to the slope of the land surface. Topography helps to control that a pollutant runs off or remains on the surface in one area long enough to infiltrate. Topography influences soil development and therefore have an effect on contaminant attenuation. A Digital Elevation Map of the area was used to represent the topography of the study area. The basin drops from the central highlands in a general southerly direction, towards the lower basin, which consists of very gentle and flat lands. The prominent feature is that, having high elevations on the western part of the basin and having very flat plains with elevations of 100 to 200m found in the eastern part of the basin (Kulatunga, N., 1998). Since the steepness of the topography is less, and compared to the ranges given in DRASTIC scheme, this slope is very low and high pollution potential can be suspected, and hence higher ratings were assigned (Table 1).

The vadose zone is defined as the zone above the water table which is unsaturated or discontinuously saturated. The type of vadose zone media determines the attenuation characteristics of the material below the typical soil horizon and above the water table. Biodegradation, neutralization, mechanical filtration, chemical reaction, volatilization and dispersion are all processes, which may occur within the vadose zone. The vadose zone was classified according to the data obtained from well log records. Considering relevant properties, the relative ratings were assigned for each group (Table 2).

Hydraulic conductivity refers to the ability of the aquifer materials to transmit water, which in turn, controls the rate at which groundwater will flow under a given hydraulic gradient. The rate at which the groundwater flows also controls the rate at which a contaminant moves away from the point at which it enters the aquifer. Hydraulic conductivity is controlled by the amount of interconnection of void space within the aquifer. To calculate the hydraulic conductivity, several pumping test data, carried out in the study area were used. Even though the number of test data was less, the available hydraulic conductivity values were grouped into ranges and the ratings were assigned where high conductivity is associated with high pollution potential (Table 1).

Table 1. Ranges and ratings for depth to groundwater table, net recharge, topography and hydraulic conductivity.

Depth to water table		Net Recharge		Topography (slope)		Hydraulic Conductivity	
Range (m)	Rating	Range (mm)	Rating	Range (% slope)	Rating	Range (m/day)	Rating
0 – 1.5	10	0-25	1	0.002 - 0.2	10	0 - 5	1
1.5 – 4.5	9	25-50	3	0.2 – 1.0	9	5 - 10	2
4.5 – 9.0	7	50-75	6	1.0 – 2.5	7	10 - 15	4
9.0 – 15.0	5	75-100	8	2.5 – 3.5	5	15 - 20	6
15.0 –22.0	3	100>	9	3.5 – 4.5	4	20 - 25	8
22.0 – 30.0	2			4.5 >	3	25 >	10
30.0 +	1						

Table 2. Ranges and ratings for aquifer Media, soil type and vadose zone media

Aquifer Media		Soil type		Vadose Zone Media	
Range	Rating	Range	Rating	Range	Rating
Quartzites and Pegmatite	2	Clay	1	Fresh rock	1
Regolith	3	Sandy Clay	2	Sand, silt and clay	3
Crystalline limestone.	6	Organic/decomposed materials	3	Biotite (Metamorphic rock)	4
Littoral sands	6	Clayey sand	6	Sand and Gravel	6
Alluvium	8	Clay with quartz and gravel	7	Limestone	6
Sand and Gravel	8	Gravelly sand	9	Boulders / Rubbles	9
Major faults, joints	10				

After assigning the ratings for each of the seven DRASTIC features, the next step was to develop the DRASTIC index according to the importance of the parameters to the pollution. Each DRASTIC parameter has been evaluated with respect to the others in order to determine the relative importance of them. The DRASTIC Index, a measure of the pollution potential, is computed by summation of the products of rating and weights of each factor. Thus, each parameter has a predetermined, fixed, relative weight that reflects its relative importance to vulnerability. The most significant factors have weights of 5; the least significant a weight of 1 (Table 3). Each factor is assigned a weight based on its relative significance in affecting pollution potential. The DRASTIC Index is computed by summation of the products of rating and weights of each factor.

To create the DRASTIC Index map, the study area was divided into 500 m × 500 m grids. The resulting map of the DRASTIC index to represent the groundwater vulnerability has been calculated by the operation of map overlays and classification performed in the GIS environment. After processing of the seven DRASTIC parameters into cell vector map layers using ARC/INFO, the layers were converted to ERDAS GIS raster format. The step-by-step procedure was followed to overlay each of the features as explained in the methodology. The ultimate result is a numerical value; the DRASTIC Index (DI) for each cell has been calculated using the additive equation.

Table 3. The weighting factors for hydro-geological variables in DRASTIC method

Hydro-geological variable	Weighting Factor
Depth to Groundwater (D)	5
Net Recharge (R)	4
Aquifer media (A)	3
Soil media (S)	2
Topography (T)	1
Impact of the Vadoze zone (I)	5
Hydraulic Conductivity (C)	3

RESULTS AND DISCUSSIONS

Final DRASTIC coverage shows the distribution of DRASTIC vulnerability index over the study area (Figure. 2). The DRASTIC index ranges between 89 and 197 which are compatible with the range given by Aller et al, (1987); within the range 50 to 200. The DRASTIC index was further divided into five categories: very low, low, moderate, high, and very high. The higher DRASTIC index means the greater relative pollution potential. The classification is based in the DRASTIC Index as follows,

- Very low vulnerability (DI < 100)
- Low vulnerability (100 < DI < 125)
- Medium vulnerability (125 <DI <150)
- Moderately high vulnerability (150 <DI < 180)
- High vulnerability (DI > 180)

The DRASTIC indexes are relative values and, a site with low index need not necessarily mean that it is free from groundwater contamination, but it is relatively less susceptible to contamination compared to the sites with high or very high DRASTIC index. Figure 2 shows that the values of the DRASTIC index clusters around moderate vulnerability with very few points in the low and high vulnerability ranges. It favourably shows that the lower part of the basin is exposed to higher vulnerability while the upper eastern part has very low and low vulnerability. The central region of the basin covers with medium to moderate vulnerability.

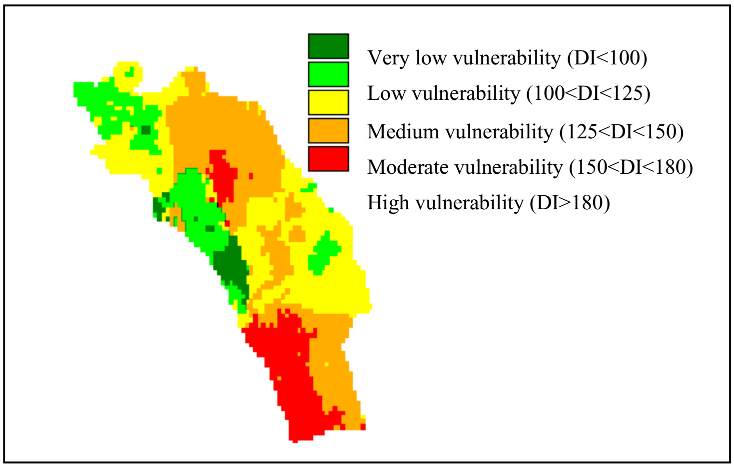

Figure 2. Resultant DRASTIC map

GROUNDWATER VULNERABILITY AND LAND USE PATTERN

To incorporate the impact of land use activities with extensive fertilizer usage over prolonged periods of time, the land use pattern of the area has been evaluated with DRASTIC maps. For this purpose, the land use data for the area were obtained from the maps of Geological Survey and Mines Bureau, Sri Lanka. The land use coverage can be classified in to five main groups based on the land use infiltration; paddy fields, impervious areas or gardens, forests, reservoirs or waterways and other agricultural areas. The other agricultures are sugar cane, chena (dry-land cultivation) and upland crops. The forests mainly consist of marshy lands, scrubs, grass lands and mild and thick forests (Figure 3).

Most of the paddy fields are located in the lower part of the basin. The flat and gentle lands in the lower basin are suitable for paddy cultivation. There is an underlying alluvial deposit layer in almost all paddy field areas (Jayaweera, U., 1999). This alluvial layer leads to a higher infiltration of contaminant to deep groundwater. The other agricultural crop areas especially dry-land cultivations are also identified as active non-point sources of groundwater contamination. There is higher infiltration occurring in agricultural crop areas such as upland crop fields due to high permeable soil layers. Human activities in agricultural fields, mainly the over use of fertilizers and pesticides, affects the groundwater contamination and those areas can be considered as areas where the levels of risk to groundwater from potential pollution expected to be high. The forests with less anthropogenic activities have less pollution potential. The forests are mainly distributed in the upper part of the basin and the upper area has steep slope and higher depth for groundwater level.

The values of the DRASTIC index also favourably show that the lower part of the basin is exposed to higher vulnerability while the upper and eastern areas are exposed to low and very low vulnerability. It is noticed that the paddy fields and other cultivation areas are overlapped with the higher DRASTIC index regions, which show the highest potential for the vulnerability (Figure 3). These are the areas where percolation of pollutants to groundwater is enhanced. The areas with both higher DRASTIC index and extensive agricultural usage have the maximum potential for groundwater pollution. Thus an effective use of composite DRASTIC and land use assessments can assist in assessing the groundwater vulnerability and planning guidelines which take into account the hydrological realities as well as human activities.

The anthropogenic stress of highly vulnerable areas such as usage of fertilizers and pesticides must be managed and controlled to protect the contamination of groundwater resources. Attention must be focused to the areas with extensive land use activities and the human activities, mainly the over use of fertilizers and pesticides for the crops, sewerage facilities, landfills and waste disposal activities. While making the land use control policies, these ground water vulnerability maps are very useful to take appropriate decisions and subsequent measures for pollution prevention and mitigation.

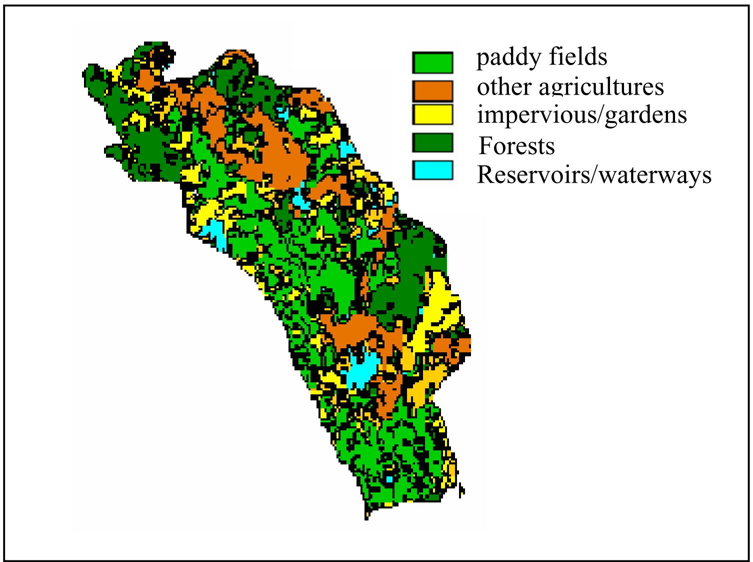

Figure 3. Land use in Walawe River Basin

CONCLUSIONS

Among the methods for measuring groundwater vulnerability, DRASTIC index is a feasible indicator to understand groundwater vulnerability, based on the physical setting of the groundwater system and it was successfully applied to Walawe river basin to develop groundwater vulnerability maps. Localized ranges and ratings have been used where required, to implement and adopt data according to local conditions. The resultant DRASTIC indexes for the entire study area reflect mostly low to moderate vulnerability while the lower part of the basin is exposed to higher vulnerability and the upper eastern part of the area has low and very low vulnerability. The high and very high vulnerable areas are coincident with the paddy cultivated lowland areas with the terraces build from alluvial deposits and shallow groundwater table. In such areas, the density of monitoring points for adequate groundwater quality control must be enhanced and land use guidelines and limitations must be carefully drawn up to control the groundwater contamination and to protect the groundwater resources for sustainable groundwater usage strategies.

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