Determination of the radius of influence for groundwater sources using a spatial mapping method

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Highlights

- Groundwater quality parameters of pH, BOD₅, COD and DO are not within the limits of the drinking water standards.
- Built-up areas within 200 m may have higher influence on BOD₅ and COD levels of the wells.
- Runoff from built-up areas could be a prominent non-point source of pollution to the groundwater.
- Agricultural land uses within 500 m buffer zone may have significant impact on pH of the groundwater.
- Long term intensive agricultural practices may have caused lower pH levels.

RESEARCH ARTICLE

Determination of the radius of influence for groundwater sources using a spatial mapping method

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Abstract: The radial distance over which a particular land-use has the major influence on the groundwater quality is known as the radius of influence (ROI). For this study, total of 39 open well sampling sites were selected across the 13 DSDs in Colombo district. Landsat 8 OLI/TIRS image was acquired and supervised classification was employed to classify land-uses into four major categories. From each well, buffer zones were created at 100 m interval from 0 to 500 m. Following that the intersect tool was applied at each buffer zone to calculate the areas of intersecting land-uses. Simple regression analysis between higher percentage land-use and parameters were conducted to find the optimum radius of influence. The results of groundwater quality revealed that COD, BOD₅, DO and pH levels in some wells were not meeting the standard levels of 15, 3, 6 mg L⁻¹ and 6-8.5 respectively. Most of the wells with higher COD and BOD₅ have higher percentage of impervious areas. Highest co-efficient for COD, 0.23 ($p < 0.05$) at 200 m radius and for BOD₅, 0.05 ($p < 0.05$) at 200 m radius were obtained. Low pH values were observed in intense agricultural areas and at 500 m radius, highest co-efficient of 0.037 ($p < 0.05$) was obtained. Correlations between COD and BOD₅ concentrations with impervious areas were low (R^2 ; 11% and 21% respectively) even at significant level of 0.05 but correlation between pH and vegetated areas was comparatively higher (R^2 ; 40.9%). The study suggests that sustainable land-use management practices should be carried out to protect the groundwater resources.

Keywords: Landsat; GIS; groundwater quality; ROI; remote sensing.

INTRODUCTION

The usage of groundwater in Sri Lanka steadily increases due to rising demand for freshwater resources in urban & rural water supplies, irrigated agriculture and the industrial sector. Especially in districts like Colombo, individual domestic use is estimated to be millions of cubic meters annually (Herath, 2007). This rapid increase in demand is exerting a significant pressure on the available groundwater resources. At the same time, groundwater in Colombo district suffers from many kinds of contamination from both natural and anthropogenic sources which have a direct relation to the land use of the area (Scanlon *et al.*, 2005).

Various methods are available to delineate areas which

influence the quality of groundwater. Among them, the following methods are used in common; arbitrary radial distance is a simple method, comprised of fixed radius circles around the well. This fixed radius can be estimated by assessing local hydrological factors including soil porosity, flow rate of groundwater, etc. Due to its simplicity, this method may overprotect or under protect specific areas (Fileccia, 2015). Calculated fixed radius method defines a circular area around the well which is determined by an algebraic equation of Time of Travel (TOT), which uses data such as pumping rate and aquifer porosity. While it takes some aquifer properties into calculation, its tendency to generalize factors may lead to uncertainty, especially in heterogeneous subsurface (Miller *et al.*, 2003).

Solute transport processes use computer models to determine groundwater or contaminant flow but they require a significant amount of input data. Hydrogeologic mapping uses geological or geophysical data to delineate specific areas. This method demands considerable professional expertise and access to various geologic data, but is suitable in areas with complex geologic formations (Samani and Garcia, 2014; Kourgialas *et al.*, 2017).

The selection of an appropriate method depends on a range of factors, including access to hydrological data, cost, technical resources and availability of specialized knowledge. In this study, an attempt has been made to determine the radius of influence using a novel and simple method by partially combining available methods. The accuracy of the method is increased by using Satellite images to classify land uses and the actual quality of the groundwater is correlated with land uses. The Landsat satellite images provide an excellent spatial-temporal feature and it is also freely available in the public domains (Vanjare *et al.*, 2014). A range of key physicochemical parameters which can indicate the drinking water quality are selected to check if their values are in higher concentrations than the safe limits by the proposed ambient water quality standards. Eventually, a correlation was developed between the two factors to delineate the optimum radius which may significantly influence groundwater quality. Through this study, the importance of protecting groundwater sources by managing land uses can be emphasized.

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MATERIALS AND METHODS

Colombo District was the target area for this study. It is located in the western province of Sri Lanka (latitude 80.0535° E, longitude 6.8602° N). The district is divided into 13 divisional secretariat divisions (DSD). Total land area of the division consists approximately 699 square kilometers with total population of 2,375,000 inhabitants (Department of census and statistics, Sri Lanka, 2015).

Data collection

Selecting groundwater sampling sites

From each DS division, three locations were selected randomly according to the availability of open wells to cover the entire DS division. Altogether 39 locations were selected (Figure 1) and sampling sites were referenced to their positions using global positioning system (GPS). Sampling sites were named as follows; Awissawella (A1, A2, A3), Padukka (P1, P2, P3), Homagama (H1, H2, H3), Kaduwela (K1, K2, K3), Maharagama (M1, M2, M3), Kesbawa (KS1, KS2, KS3), Moratuwa (MO1, MO2, MO3), Rathmalana (R1, R2, R3), Dehiwala (D1, D2, D3), Wellawatta (W1, W2, W3), Colombo (C1, C2, C3), Kollanawa (KO1, KO2, KO3), Kotte (SJ1, SJ2, SJ3).

Physicochemical parameters for groundwater quality assessment

Sampling was carried out during the south western monsoon from June to September 2018. From each DS division three well water samples were collected randomly with three replicates from each well at once. Samples were collected between 0-3 m depths from open wells, preserved and transported to the laboratory of the Department of Zoology and Environmental Management. Samples were stored at 4 °C temperature until the standard laboratory testing was conducted. Calibrated Multimeter HACH/Model: Hq40d

multi parameter was used to test in-situ physicochemical parameters (pH, electrical conductivity, total solids, salinity, dissolved oxygen and temperature) and ex-situ physicochemical parameters (chemical oxygen demand, biochemical oxygen demand, total hardness, nitrate nitrogen concentration, total phosphate) were measured using APHA standard methods (APHA, 1998).

In order to produce Land Use Land Cover (LULC) map of the study area, following data were collected. Administrative boundary shape file of Colombo district was obtained from the Survey Department, Colombo, Sri Lanka. Radiometrically calibrated, orthorectified and highest quality level 1 Landsat satellite scenes for the year of 2018 were ordered and downloaded from USGS Earth Explore website (<http://earthexplorer.usgs.gov/>).

Data analysis

The useful single band raster data sets of Landsat scene were selected and composited to get a multiband raster data set. Following the composition, the study area was extracted using Colombo district shape file. Maximum likelihood supervised classification technique was used to produce satellite derived LULC maps (Antalyn and Weerasinghe, 2020). Landsat satellite data of 2018 year was analyzed by using ArcGIS version 10.2.2.

Following the classification, the classified raster image was converted into vector format using raster to polygon tool (conversion). Multiple Buffer zones (100, 200, 300, 400 and 500 m) were created to groundwater sampling points at 100 m intervals to calculate the area of intersecting land uses. The Figure 2 shows the steps involved in intersecting land use calculation. Groundwater physicochemical parameters were compared with proposed ambient water quality standards by CEA. Physicochemical parameters which were exceeded the standards, were selected for the regression analysis.

Figure 1: Groundwater sampling sites of the Study area.

Figure 2: The steps involved in intersecting land use area calculation.

Figure 3: Vector map of LULC classes of Colombo district in 2018.

In each buffer zone percentage of area extend of four land use classes were calculated. Simple regression analysis between higher percentage land use class in each buffer zone and exceeded groundwater quality parameters were conducted to find the highest co-efficient and optimum radius of influence (Lee *et al.*, 2003).

$$Y = MX + C \dots\dots\dots (1)$$

In the regression equation 1, Y is represented by a physicochemical parameter that exceeds or did not meet the standards. The coefficient (M) shows whether there is a positive or negative correlation between independent and the dependent variable also explains the mean increase or decrease of physicochemical parameter for every additional one percentage of a land use. X is a particular

land use area percentage in considered buffer zone and C is a constant. P value is used to explain the significance of the relationships.

RESULTS AND DISCUSSION

Accurate LULC maps can play an important role in aiding proper land use management practices which can leads to the protection of precious groundwater resources. Figure 3 shows the results of the supervised classification using maximum likelihood classifier. The total area extended within the study area was 36.3, 276.8, 247.0 and 117.4 km² for water body, built-up, vegetation and forest respectively. Built-up area percentage is the highest in Colombo district while water bodies are the least area.

Figure 4: LULC maps with mean values of (a) pH, (b) BOD₅, (c) COD and (d) DO at the sampling points of DSDs.

Groundwater quality parameters of pH, BOD₅, COD and DO were not within the standards. The BOD₅ values of the wells ranged from 0.95 ± 0.02 to 11.87 ± 0.14 mg L⁻¹. The COD values of the wells ranged from 5.95 ± 0.81 to 89.54 ± 3.87 mg L⁻¹. The DO values of the wells ranged from 0.98 ± 0.02 to 10.64 ± 0.02 mg L⁻¹. The pH values of the wells ranged from 2.62 ± 0.22 to 7.09 ± 0.31 and the standard levels for BOD₅, COD, pH and DO were 3 mg L⁻¹ (standard upper limit), 15 mg L⁻¹ (standard upper limit), 6.5 – 8.0 and 6 mg L⁻¹ (standard lower limit) respectively.

pH is the index indicating acidity or alkalinity of water. According to the results, wells surrounded with built-up areas showed pH fall within the standard range of 6.5 to 8, but wells in agricultural areas show below standard values (Figure 4a). This can be due to the natural acidification, including the pH values of red-yellow podzolic soils (generally below 6 and often below 5.5) (Moorman and Panabokke, 1961) and acidification from the precipitation, which in its natural state has a pH value around 5.6.

However, pH values in vegetative areas show a significantly lower value ranged between 2.62 and 6.71 and most of them were below pH 5. The lower pH levels may be due to the intensive cultivation in agriculture and forestry over a long period which may cause acidification of soils by nutrient uptake of bases (Knutsson, 1994; Mikunthan *et al.*, 2013).

Biological oxygen demand (BOD₅) and chemical oxygen demand (COD) are globally used in water quality parameters for the evaluation of organic contaminant pollution in water environment (Lee *et al.*, 2016). If COD or BOD₅ values are high, the water is rich in organic matter and other oxidizable components (APHA, 1998) which indicate pollution. According to proposed ambient water quality standards the standard level of COD and BOD₅

should be below 15 mg L⁻¹ and 3 mg L⁻¹ respectively for drinking purpose. But most of the sampling points were above the limit and highest mean values were observed in built up areas (Figure 4b and c). The reasons might be due to high organic matter accumulation by high urban runoff and sewage seepage from slums (Fineza *et al.*, 2014).

High levels of DO show higher dissolved oxygen levels indicating a better water quality. When microbial activity and organic matter content increase, DO would decrease. Also, DO is directly affected by the level of temperature. According to proposed ambient water quality standards, the standard level of DO should be above 6 mg L⁻¹ for drinking purpose. Low DO could be an indicator of microbial activity and high organic matter content. Among the sample wells, 90% of them were below the standard level. This might be due to their stagnancy and low interface with the atmosphere of deep wells. No certain pattern was observed in DO distribution in the study area in Figure 4d.

Built up and vegetated areas were the major land use types dominant around the sampling wells. Therefore, the influence by these major land uses could be significant. COD and BOD₅ levels did not meet the standard levels in most of the wells surrounded by built up areas indicating that the particular land use could be a prominent non-point source pollution to the wells. On the other hand, pH levels were low in most of the wells surrounded with vegetated areas and among them; agricultural practices are shown to be intensive in these areas.

Regression analysis was performed between concentrations of BOD₅ in wells and built up area percentage in each buffer zone. Significant and highest coefficient was found in 200 m buffer zone which indicated that land-uses within 200 m have a higher influence in BOD₅ levels of wells. Similarly, regression analysis between

Figure 5: Intersecting land uses at selected buffer zones from a sampling point.

Figure 6: Regression coefficient variation for groundwater quality parameters by increment of radius of influence. Highest coefficient for COD, 0.23 ($p = 0.039 < 0.05$) at 200 m radius and for BOD₅, 0.05 ($p = 0.003 < 0.05$) at 200 m radius with built-up areas. Highest coefficient for pH, 0.037 ($p = 0.000 < 0.05$) at 500 m radius with vegetated areas.

percentages of built up areas and COD levels disclosed that land-uses within 200 m buffer zone have a higher influence in determining COD levels. Further, analysis between pH levels and vegetative areas revealed that land-uses within 500 m buffer zone have significant impact in pH of groundwater. (Figure 6, Table 1). No significant correlation was found between DO and land uses at any considered radius.

Correlation results between BOD₅, COD concentration and land-uses are shown to be low and weak even at a

significant level of 0.05. The R^2 values from the regression analysis also show very low correlation of 21.9% and 11% respectively. These results suggest that many contaminant sources may exist in addition to the considered land uses. But correlation results between pH and land uses showed comparatively higher R^2 value of 40.9% which indicates higher influence of agricultural practices in the pH of groundwater.

Table 1: As significant and highest coefficient was found in 200 m with COD, BOD₅ and 500 m buffer zones with pH, the table shows the major land use classes and their percentages in the particular buffer zones

Sampling points	Major land use type		COD(mg L ⁻¹)	BOD ₅ (mg L ⁻¹)	pH
	Built up % / 200 m	vegetation % / 500 m			
A1	13.82	68.64	14.9	2.1	4.94
A2	7.80	61.97	15.9	1.7	4.61
A3	78.42	35.43	21.8	2.5	4.23
C1	92.20	4.55	11.3	1.7	6.77
C2	90.59	9.46	30.1	6.2	6.33
C3	99.88	0.00	15.1	1.9	7.09
D1	98.01	0.00	45.2	7.9	6.43
D2	99.88	5.48	52.8	2.2	6.78
D3	99.88	2.28	7.5	7.6	6.14
H1	23.13	75.49	17.5	3.1	4.51
H2	70.59	54.43	10.7	1.3	3.26
H3	43.84	42.95	19.4	4.1	4.37
K1	99.16	17.34	10.9	2.8	3.57
K2	93.72	16.70	6.9	2.2	4.60
K3	57.22	35.79	8.9	2.0	3.85
KO1	55.60	33.03	7.5	3.4	6.06
KO2	92.62	10.19	7.5	3.7	6.49
KO3	88.27	3.55	30.1	3.0	6.71
KS1	81.55	32.81	59.5	9.8	3.34
KS2	53.41	34.46	19.8	3.1	3.64
KS3	74.82	31.35	39.7	3.5	2.69
M1	83.12	27.81	16.5	5.1	4.60
M2	83.02	33.51	20.4	7.0	4.26
M3	88.59	14.62	19.8	6.1	4.56
MO1	99.88	7.48	19.8	4.0	3.33
MO2	76.58	25.97	59.5	6.7	3.34
MO3	96.85	0.11	79.4	10.6	6.34
P1	34.02	61.63	14.9	1.4	3.85
P2	0.19	56.09	6.0	1.3	2.62
P3	5.40	65.13	10.9	1.0	3.67
R1	96.30	2.73	20.8	2.9	5.54
R2	98.45	0.34	27.8	3.9	5.27
R3	99.88	2.15	20.8	4.1	5.78
SJ1	68.89	22.85	26.4	3.9	6.53
SJ2	84.22	33.91	45.2	6.2	5.37
SJ3	99.88	0.00	37.7	3.4	5.77
T1	99.17	1.68	22.6	8.0	6.48
T2	98.45	1.41	22.6	9.3	6.53
T3	97.53	1.42	98.0	12.4	6.65

CONCLUSION AND RECCOMANDATION

The study suggests that the sustainable land use management practices including improved drainage network for urban runoff discharge, reduced unplanned development, conducting inventory of potential contaminant sources and their management should be carried out to protect the groundwater resources. BOD₅ and COD levels of wells may be affected by runoffs from built up areas within 200 m radius. pH of wells may be affected by intensive agricultural activities in 500 m buffer zone in Colombo district. DO levels may not have a significant impact by land uses. Further, proper public education and awareness programs should be conducted to the abounding people who are dependents of groundwater for drinking purpose. Since this study did not consider factors influencing the groundwater quality i.e. groundwater flow, flow rate, subsurface condition, in future studies these aspects can be included to improve the accuracy of the findings. Higher resolution images can be used to classify more LULC classes to detect exact practices which will lead to contamination of groundwater and further studies are encouraged to execute with more sampling points. Findings of this research can be used for urban planning and sustainable development in Colombo district.

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DECLARATION OF CONFLICT OF INTEREST

The authors declare no competing interests.

REFERENCES

- Antalyn, B. and Weerasinghe, V.P.A. (2020). Assessment of Urban Sprawl and Its Impacts on Rural Landmasses of Colombo District: A Study Based on Remote Sensing and GIS Techniques. *Asia-Pacific Journal of Rural Development* **30**: 139-154. DOI <https://doi.org/10.1177/1018529120946245>.
- APHA, (1998). Greenburg A.E., Rhodes T.R. and Lenore S.C. Standard Methods for the Examination of Water and Waste water, 20th edition, APHA/AWWA/WEF.
- Department of census and statistics, (2015). Census of population and housing. Available from <http://www.statistics.gov.lk/page.asp?page=Population%20and%20Housing> (22 October 2018).
- Fileccia, A. (2015). Some simple procedures for the calculation of the influence radius and well head protection areas (theoretical approach and a field case for a water table aquifer in an alluvial plain). *Acque Sotterranee-Italian Journal of Groundwater* **4**(3):7-23. DOI <https://doi.org/10.7343/as-117-15-0144>
- Fineza, A.G., Marques, E.A.G., Bastos, R.K.X. and Betim, L.S. (2014). Impacts on the groundwater quality within a cemetery area in southeast Brazil. *Soils Rocks* **37**(2): 161-169.
- Herath, G. (2007). The Study of the Management of Groundwater Resources in Sri Lanka. IGES: *Sustainable Groundwater Management in Asian Cities-a final report on Sustainable Water Management Policy*, 110-136.
- Knutsson, G. (1994). Acidification effects on groundwater-prognosis of the risks for the future. *IAHS PUBLICATION*, Pp.3-3.
- Kourgialas, N.N., Karatzas, G.P. and Koubouris, G.C., (2017). A GIS policy approach for assessing the effect of fertilizers on the quality of drinking and irrigation water and wellhead protection zones (Crete, Greece). *Journal of Environmental Management* **189**: 150-159. DOI <https://doi.org/10.1016/j.jenvman.2016.12.038>.
- Lee, J., Lee, S., Yu, S. and Rhew, D. (2016). Relationships between water quality parameters in rivers and lakes: BOD₅, COD, NBOPs, and TOC. *Environmental Monitoring and Assessment* **188**(4): 252. DOI <https://doi.org/10.1007/s10661-016-5251-1>.
- Lee, S.M., Min, K.D., Woo, N.C., Kim, Y.J. and Ahn, C.H. (2003). Statistical models for the assessment of nitrate contamination in urban groundwater using GIS. *Environmental Geology* **44**(2): 210-221. DOI <https://doi.org/10.1007/s00254-002-0747-0>.
- Mikunthan, T., Vithanage, M., Pathmarajah, S., Arasalingam, S., Ariyaratne, R. and Manthirithilake, H. (2013). Hydrogeochemical characterization of Jaffna's aquifer systems in Sri Lanka. Colombo, Sri Lanka: *International Water Management Institute (IWMI)*. Pp. 69.
- Miller, C., Chudek, P. and Babcock, S. (2003). A comparison of wellhead protection area delineation methods for public drinking water systems in Whatcom county, Washington. *Journal of Environmental Health* **66**(2):17-24.
- Moorman, F.R. and Panabokke, C.R. (1961). Soils of Ceylon. *Tropical Agriculture* **117**(I): 22-23.
- Samani, Z. and Garcia, J., (2014). Wellhead protection for water wells. *Hydraulics of Wells: Design, Construction, Testing, and Maintenance of Water Well Systems* **127**: 315.
- Scanlon, B.R., Reedy, R.C., Stonestrom, D.A., Prudic, D.E. and Dennehy, K.F. (2005). Impact of land use and land cover change on groundwater recharge and quality in the southwestern US. *Global Change Biology* **11**(10): 1577-1593. DOI <https://doi.org/10.1111/j.1365-2486.2005.01026.x>.
- USGS, (2018). Data and tools. Available from <https://www.usgs.gov/land-resources/nli/landsat/data-tools> (12 November 2019).
- Vanjare, A., Omkar, S.N. and Senthilnath, J. (2014). Satellite Image Processing for Land Use and Land Cover Mapping. *International Journal of Image Graphics and Signal Processing* **6**(10): 18-28. DOI <https://doi.org/10.5815/ijigsp.2014.10.03>.