DELINEATING GROUNDWATER VULNERABILITY IN METRO CEBU USING DRASTIC MODEL

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ABSTRACT: Metro Cebu's groundwater sources, especially in the coastal areas, are already threatened because of excessive consumption, contamination, and saltwater intrusion. Rapid urban expansion has also inflated the inherent vulnerability of the metropolitan area's groundwater sources in addition to the apparent shortage of the resource. Thus, solutions such as the utilization of remote sensing (RS) and geographic information systems (GIS) for the selection of priority areas for groundwater protection are valuable. In the current study, the intrinsic vulnerability of groundwater from contaminants emerging from the surface was spatially defined for Metro Cebu. This was achieved by developing a groundwater vulnerability map using the DRASTIC model which is an integration approach incorporating spatial information such as depth to water, net recharge, aquifer media, soil media, impact of vadose zone, and hydraulic conductivity. The resulting map classified the study area into very low, low, moderate, high, and very high groundwater vulnerability zones. About one-third of Metro Cebu lies in high (24.77%) and very high (7.17%) vulnerability zones. Meanwhile, areas in very low, low, and moderate vulnerability cover 14.91%, 33.28%, and 19.87%, respectively. Analysis of the map revealed that areas included in high to very high groundwater vulnerability classes were nearshore plains which were characterized by shallow depth to water, moderate to high annual recharge, alluvium and karstic limestone geologic units, clay loam soil texture, and gentle slopes. Evidently, RS and GIS integration techniques provided an appropriate and low-cost tool for targeting priority areas for groundwater protection, water quality monitoring, wastewater treatment facility planning in Metro Cebu through the development of the vulnerability map.

1. INTRODUCTION

Water is a critical resource at the center of rapidly growing urban centers such as Metro Cebu in the Philippines. A study from the Japan International Cooperation Agency (JICA) estimates the water demand at 227,000 cubic meters/day in 2013 and projects a demand of 797,000 cubic meters/day by 2050 (Nagayama, 2015). Metro Cebu Water District (MCWD) in 2019 estimated that groundwater extraction in the urban center has already peaked to 400,000 cubic meters/day.

Rapid urban expansion has exacerbated the inherent vulnerability of the metropolitan area's groundwater sources in addition to the apparent shortage of the resource. Ensuring adequate water supply and its healthy quality are among the major themes of Cebu's development roadmap for 2050. Limitations cited in the roadmap include an expanding water supply and demand gap, saltwater intrusion, and nitrate and E. Coli contamination (Nagayama, 2015). However, solutions such as wastewater treatment is currently lacking. The Cebu 2050 roadmap have modest wastewater treatment targets of 50% population coverage by 2030 and 90% yet to be achieved by 2050.

This study aims to develop a map of groundwater vulnerability by estimating the intrinsic vulnerability of the groundwater of Metro Cebu. The intrinsic vulnerability indicates the vulnerability of water to contamination (independent of the nature of pollutants) that arise from human factors in relation to the hydrological, geological, and hydrogeological attributes of the aquifer (Barbalescu, 2020). The vulnerability map can reveal locations with the highest potential for contamination of the groundwater resource (Rupert, 1999).

Understanding the present vulnerability of the water source facilitates better management and protection of the resource. By utilizing remote sensing (RS) and geographic information systems (GIS) integration techniques, the metro-wide analyses will be a tool for appropriate government interventions such as the identification of priority zones for water protection, monitoring sites, and strategic areas for wastewater treatment facilities.

2. MATERIALS AND METHODS

2.1 Study Area

The study covers Metro Cebu, which is an urban center located in the Central Visayas region of the Philippines (See Figure 1). Metro Cebu comprises seven cities and six municipalities spanning a land area of around 1,063 square kilometers. Population in the study area is estimated by the Philippine Statistics Authority at 3.17 million as of May 2020.

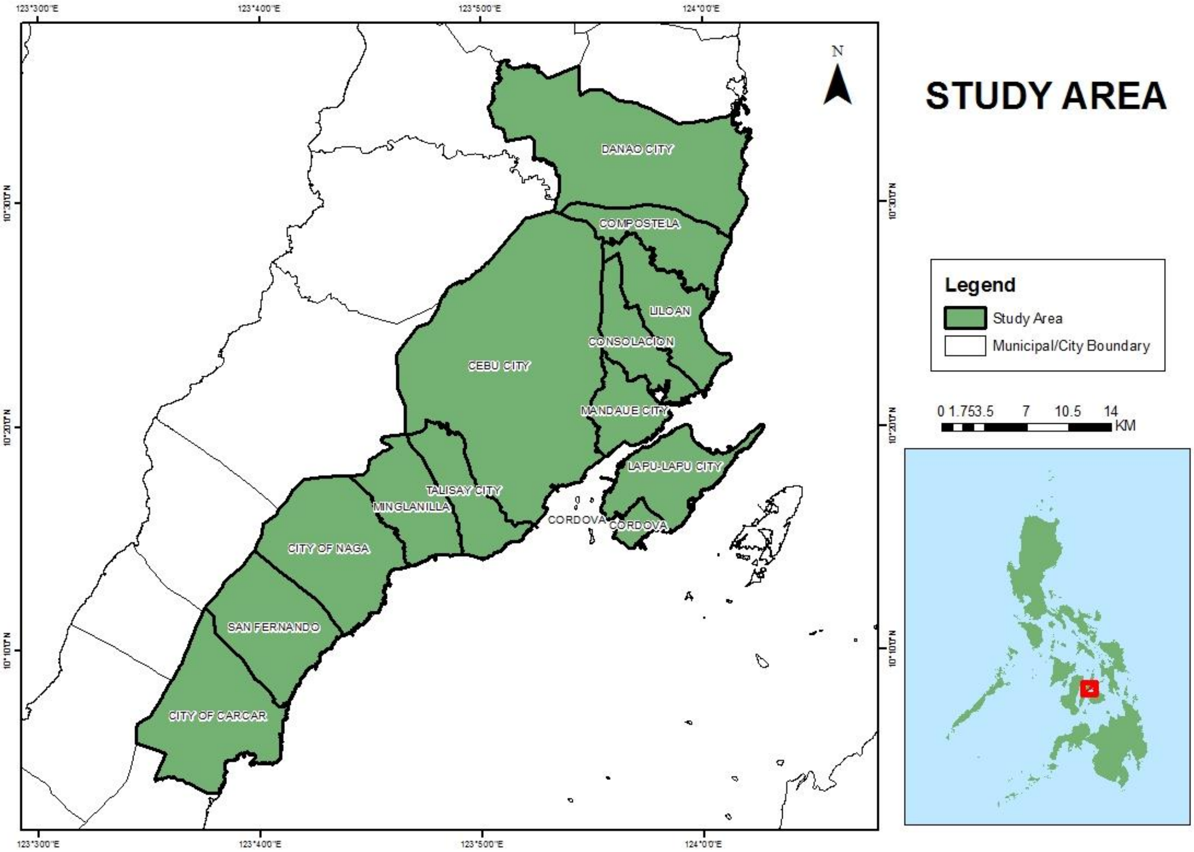

Figure 1. Location of the study area, Metro Cebu, in central Philippines is shown by red polygon.

2.2 Methods

The DRASTIC method, which is utilized by this study, is a weighted overlay approach that combines spatial data on depth to groundwater (D), recharge (R), aquifer type (A), soil properties (S), topography (T), impact to vadose zone (I), and hydraulic conductivity (C) (Aller et al., 1987). The method was developed by the US Environmental Protection Agency. For each criterion, a relative rating that ranges from 1 to 10 for each of its class/range was assigned. Classes/Ranges with higher ratings represent greater impact to groundwater contamination. Each criterion was also assigned a weight factor ranging from 1 to 5 which reveals its relative importance to groundwater contamination. The DRASTIC approach is considered as a standardized assessment groundwater contamination potential (Aller et al., 1987). The computation of the DRASTIC index of a location is as follows (Equation 1):

$$\text{DRASTIC index} = D_R D_w + R_R R_w + A_R A_w + S_R S_w + T_R T_w + I_R I_w + C_R C_w \quad (1)$$

where R is the rate and w is the parameter weight.

Criteria and Data Preparation

The following hydrological and geological factors were processed to align with the criteria of the DRASTIC approach which are seen to impact groundwater contamination in a location. The criteria, their corresponding weights, and the ratings for each class or range are summarized in Table 1.

1. Depth to water (D). This criterion is the measure of the vertical distance a pollutant moves through between the ground surface and the water level of the aquifer. Areas with shallower depths are deemed more vulnerable to aquifer pollution due to the shorter time needed for the contaminant to reach the aquifer.

The depth to water parameter was derived by performing co-kriging between the topography of the area defined by the LiDAR digital elevation model (DEM) and the well water levels provided by LWUA, NWRB, Toledo Water District, and LGU of Mandaue. The output provided by the empirical kriging method in ArcMap was considered as the best in terms of the standardized mean closest to zero, the average standard error nearest the root-mean-squared prediction error, and the standardized root-mean-squared prediction error nearest to 1 among the other kriging variants.

2. Net Recharge (R). This refers to the volume of precipitation that seeps into the water table from the ground.

Net recharge was derived from the method proposed by Piscopo (2001) which incorporates commonly available features (i.e., slope, rainfall, and soil permeability). Information on slope was derived from the Phil-LIDAR DEM, rainfall data was from PAGASA's climatological rainfall, and soil permeability data was based on the soil properties defined by the Bureau of Soils and Water Management.

3. Aquifer Media (A). This criterion is based on the consolidated or unconsolidated rock material that characterizes an aquifer. The fracturing or the different interconnected openings of rocks could strongly influence the introduction of contaminants into the aquifer.

The geologic map containing the bedrock and superficial geology of Cebu provided by the Mines and Geosciences Bureau (MGB) was used to acquire the aquifer media criterion.

4. Soil Media (S). This criterion considers the impact of soil on the volume of recharge that infiltrates into the ground including the vertical movement of contaminants into the vadose zone. Fine-textured soils (e.g., silts and clays) are seen to decrease soil permeability and restrict contaminant passage.

The spatial data for the soil media properties of Cebu was sourced from the Bureau of Soils and Water Management.

5. Topography (T). This criterion tells the likelihood of a contaminant to runoff or settle on the ground surface long enough to penetrate the soil. Essentially, a low slope slows ground surface flow and increases the risk of contaminant infiltration.

The topography layer was generated from the Phil-LIDAR DEM using Arcmap's Slope tool.

6. Impact to Vadose Zone (I). The type of vadose zone media determines the rate at which pollutants move through this unsaturated.

Due to unavailability of data, the aquifer media layer was used as proxy to the vadose zone layer. It was assumed that the unsaturated zone is a continuation and extension of the aquifer media. This assumption was based on a DRASTIC case study in Boracay Island (Linan et al., 2013).

7. Hydraulic Conductivity (C). This criterion refers to the ability of the aquifer material to transmit water. Similarly for contaminants, hydraulic conductivity governs the rate at which contaminants pass through the aquifer. Higher hydraulic conductivities are directly proportional to contamination potential.

Pumping tests and slug tests are deemed the reliable methods to estimate hydraulic conductivity of the aquifer (Lu, 2015). Data for hydraulic conductivity of an aquifer in Cebu are largely unavailable. Because these data are generally hard to obtain, they pose as a drawback in the DRASTIC approach (Lathamani et al., 2015).

The rating values for hydraulic conductivity were referenced from published range of values of the geologic media similar to those present in Cebu – a workaround when data is scarce as referred to by Lu (2015).

Table 1. DRASTIC weights, class/range ratings, and references.

Hydrogeologic Criterion	**Weight (w)**	**Class/Range**	**Rating (r)**	**Range and Ratings Reference**
Depth to water (D)	5	0 – 1.52 meters (m)	10	Aller et al. (1987)
		1.52 – 4.57 m	9	
		4.57 – 9.14 m	7	
		9.14 – 15.24 m	5	
		15.24 – 22.86 m	3	
		22.86 – 30.48 m	2	
		> 30.48 m	1	Aller et al. (1987)
Net Recharge (R)	4	0 – 50.8 millimeters (mm)/year	1	
		50.8 – 101.6 mm/year	3	
		101.6 – 177.8 mm/year	6	
		177.8 – 254 mm/year	8	
		> 254 mm/year	9	
		Basement Complex	3	

Aquifer Media (A)	3	Mananga Group	5	Aller et al. (1987), Jhariya et al. (2019)
		Barili Formation	6	
		Talavera Group	5	
		Carcar Limestone	8	
		Naga Group	6	
		Quartz Diorite	4	
		Quaternary Alluvium	9	
		Essentially keratophyre and andesite flows. Often with pyroclastics and chert of volcanic origin.	4	
		Intra-Miocene quartz diorite	4	
		Undifferentiated ultramafic and mafic plutonic rocks	3	
Soil (S)	2	Faraon Clay	1	Aller et al. (1987), Barbulescu (2020)
		Faraon Clay (Steep Phase)	1	
		Lugo Clay	1	
		Medellin Clay	1	
		Baguio Clay Loam	3	
		Macolod Clay Loam	3	
		Mandawe Clay Loam	3	
		Mantalongon Clay Loam	3	
		Hydrosol	9	
		Beach Sand	9	
		Mandawe Silt Loam	4	
Topography (T)	1	0 – 2 %	10	Aller et al. (1987)
		2 – 6 %	9	
		6 – 12 %	5	
		12 – 18 %	3	
		> 18 %	1	
Impact to Vadose Zone (I)	5	Basement Complex	4	Aller et al. (1987)
		Mananga Group	5	
		Barili Formation	6	
		Talavera Group	5	
		Carcar Limestone	7	
		Naga Group	6	
		Quartz Diorite	4	
		Quaternary Alluvium	7	
		Essentially keratophyre and andesite flows. Often with pyroclastics and chert of volcanic origin.	4	
		Intra-Miocene quartz diorite	4	
		Undifferentiated ultramafic and mafic plutonic rocks	4	
Hydraulic Conductivity (C)	3	Basement Complex	1	Aller et al. (1987), Holding and Allen (2015), Ariffin et al. (2016)
		Mananga Group	2	
		Barili Formation	2	
		Talavera Group	2	
		Carcar Limestone	10	
		Naga Group	2	
		Quartz Diorite	1	
		Quaternary Alluvium	4	
		Essentially keratophyre and andesite flows. Often with pyroclastics and chert of volcanic origin.	1	
		Intra-Miocene quartz diorite	1	
		Undifferentiated ultramafic and mafic plutonic rocks	1	

3. RESULTS AND DISCUSSION

The resulting map (Figure 2) classified the study area into very low, low, moderate, high, and very high groundwater vulnerability zones. Almost one-third of Metro Cebu lies in high (250.12 sq. km. or 24.77%) and very high (72.39 sq. km. or 7.17%) vulnerability zones. Meanwhile, areas in very low, low, and moderate vulnerability cover 14.91% (150.49 sq. km.), 33.28% (336.04 sq. km.), and 19.87% (200.61 sq. km.) of land area, respectively.

Analysis of the map revealed that areas included in high to very high groundwater vulnerability classes were nearshore plains which were characterized by shallow depth to water, moderate to high annual recharge, alluvium and karstic limestone geologic units, clay loam soil texture, and gentle slopes. Residential areas

Overlaying the groundwater vulnerability map with data on well locations (Figure 3) from the National Water Resources Board (NWRB) and the Local Water Utilities Administration (LWUA) shows most deep wells are within the vicinity of high (141 wells) and very high (98 wells) vulnerability classification. These numbers account for 79.93% of wells in the assessed area and aligns with the government drive to install wastewater treatment facilities. The lack of wastewater treatment coverage could potentially expose Metro Cebu's population to health problems arising from a polluted groundwater resource.

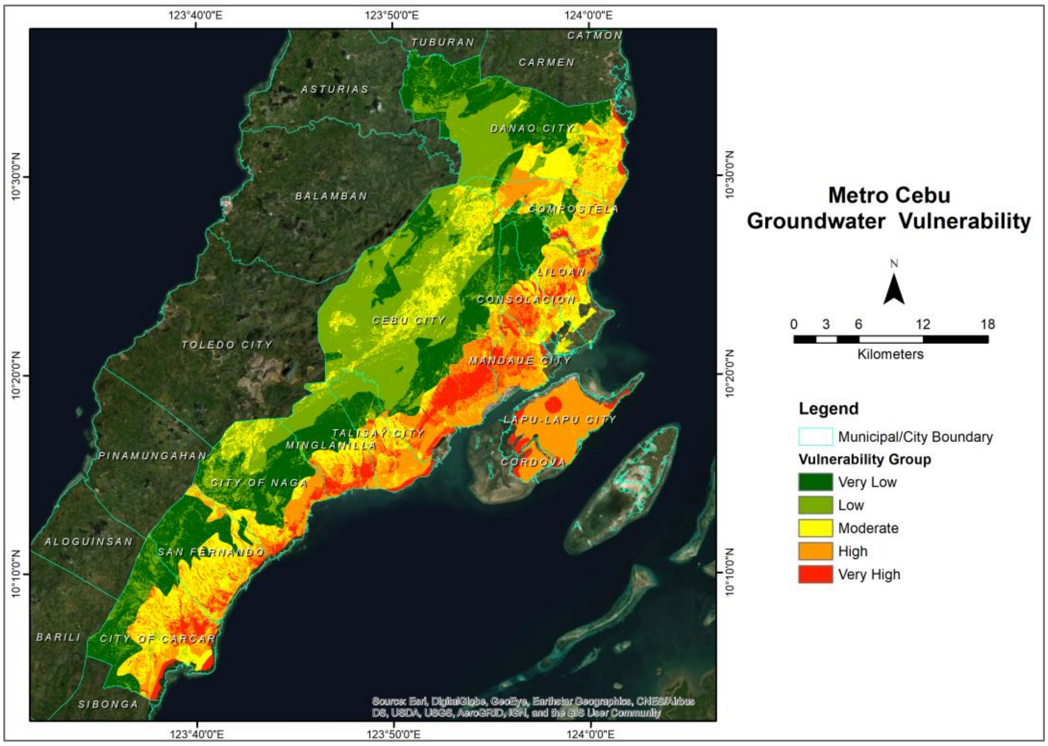

Figure 2. Groundwater vulnerability map of Metro Cebu developed using DRASTIC. Basemap Source: ESRI (2018), DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community.

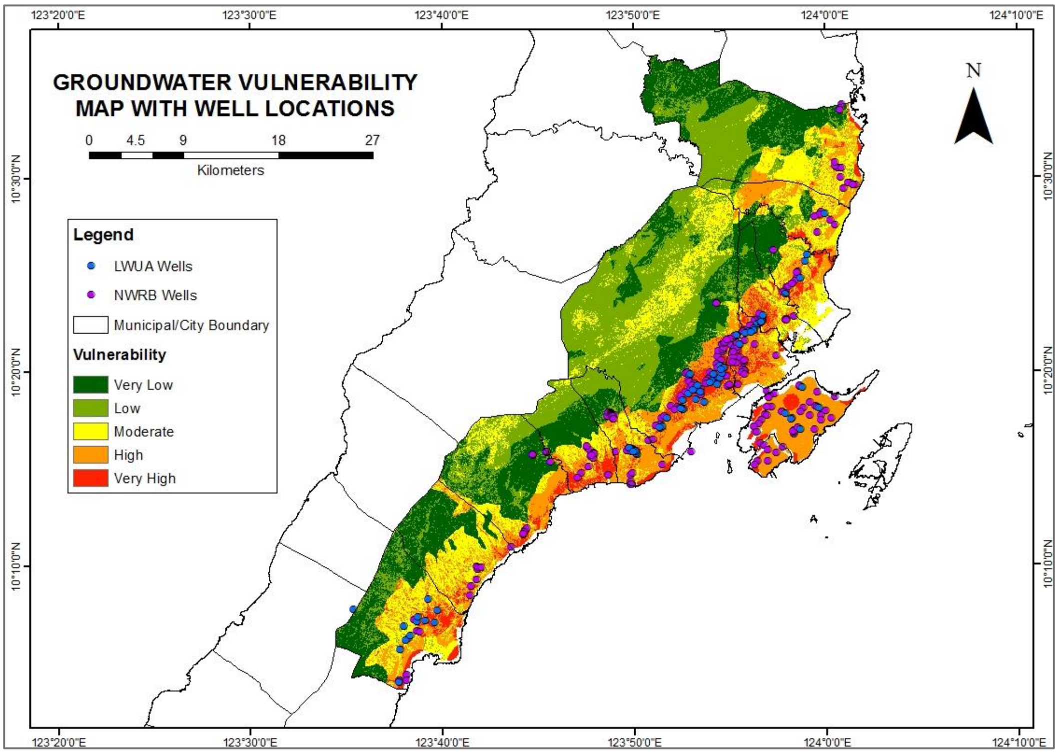

Figure 3. Locations of NWRB and LWUA-registered wells relative to the groundwater vulnerability map of Metro Cebu developed using DRASTIC.

4. RECOMMENDATIONS

Future groundwater vulnerability assessments of the study area will benefit from the acquisition of additional data to remedy the present limitations in data. The resulting groundwater vulnerability map can be a preliminary assessment resource for the local government unit and water authorities. The high overlap between existing wells and the vulnerable groundwater zones suggests the need for the identification of focus areas for preventive measures against contamination (e.g. installation of wastewater treatment facilities, regulation of potentially harmful industries) and the institution of water quality monitoring programs in strategic, highly vulnerable wells.

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