A REMOTE SENSING AND GIS-BASED CAPTURE ZONE (CapZone) APPROACH TO ASSESSMENT OF FECAL CONTAMINATION ON GROUNDWATER: A CASE STUDY OF BUTUAN CITY, PHILIPPINES

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ABSTRACT: This paper describes a method for the use of processed remotely-sensed data to infer groundwater flow directions and land cover data and the application of Remote Sensing (RS), Geographic Information System (GIS), and Multivariate Statistical Analysis (MSA) in assessing and characterizing the relationships among land cover, topographic features, well characteristics and other driving factors for fecal coliform contamination. In contrast to the conventional circular buffer zones used as GIS tool in various water quality studies, this research introduces the concept of Capture Zone (CapZone) to best characterize the potential contributing area (*pca*) to groundwater contamination. Derived regression models of FC density using the CapZone method generally yielded better R^2 values compared to the buffer method at three different radii. This suggest that the application of the CapZones as the *pca* can better characterize the influence of land cover and other causal factors to FC contamination compared to the buffer method. Furthermore, findings of this study showed that well characteristics such as depth, bottom elevation, age, and the number of persons using the well; land cover type like built-up and cropland; and slope are significant factors that can affect FC density. Thus, this study does not only prove the importance of employing RS-GIS techniques in assessing groundwater contamination but also offered a more physically plausible way of characterizing land cover influences on FC contamination to groundwater.

1. INTRODUCTION

Groundwater is often the primary source for drinking water and for domestic use. However, groundwater quality and quantity can be affected by increased demands for water (Steinman et al., 2007). Well water can become contaminated if the source aquifer is contaminated or if contaminated surface water enters the well.

Urbanization is evidently expressed in major land use changes in an area, and the influence of land use change on water sources poses an important issue, since land use is one of the factors affecting groundwater quality (B. Sarma & Saraf, 2000). Increased urbanization can lead to groundwater quality problems, as higher densities of septic systems, and a greater number of poorly maintained or failed systems, increase the risk of contamination (Steinman et al., 2007).

Fecal coliform (FC) bacteria are those that originate from intestinal tracts of homothermic animals and are used to determine fecal contamination of water. Their presence implies the potential presence of microorganisms that may cause harmful effects in humans (Entry & Farmer, 2001). Thus, fecal contamination on aquifer poses a serious threat to mankind that must be considered especially in the escalation of urbanization.

This paper describes a method for the use of processed remotely-sensed data to infer groundwater flow directions and land cover data and the application of remote sensing (RS), geographic information system (GIS), and multivariate statistical analysis (MSA) in assessing and characterizing the relationships among land use, topographic features, well characteristics and other driving factors for fecal coliform contamination. The specific objectives of this research were to show the geospatial distribution of groundwater fecal contamination; determine the influence of land cover to groundwater contamination and determine a method to characterize the potential contributing area to groundwater contamination using remotely-sensed data; and identify the causal factors to fecal contamination of groundwater in the study area.

2. BACKGROUND AND RELATED WORKS

Reddy et al. (1981) presented a good review of studies on the behavior and transport of microbial pathogens. The authors reported that retention of bacteria and viruses was found to increase with an increase in clay content and soil surface area. While Jamieson et.al, (2002) singled out moisture retention as one soil property that appears to have the greatest impact on bacterial survival, which is linked to particle size distribution and organic matter content. Further, Reddy et al. (1981) concluded that the major transport modes of pathogens and indicator organisms include movement downward with infiltrating water, movement with surface runoff water, and transport on sediment and waste particles. Jamieson et al. (2002) observed that fecal bacteria moved faster in coarser soil materials.

The potential sources of fecal contamination of freshwaters are diverse and can include point source discharges of wastewater from sewage treatment and animal processing plants, and contamination by domestic and feral animals (Wickham et al. 2006; Collins et al. 2007; Ferguson et al. 2003). Practices associated with agricultural and urban land uses are commonly reported as sources of bacterial contamination (Wickham et al. 2006; Wolf et al. 2007; Maillard & Santos 2008). Septic tank effluents may be the most significant source of pathogenic bacteria and viruses in the subsurface environment (Alley, 1993). Domestic septic system effluent typically contains about $3x10^7$ coliform bacteria/100mL and following some types of human viral infections up to $1x10^7$ virus/L (Abdel-Lah & Shamrukh 2001; DeBorde et al. 1998). According to Andrade et al. (2007), non-point sources of pollution by agriculture activities and livestock have appeared as major risks to the planet’s groundwater resources as in the works of Bouwer (2000), Chowdary et al. (2005), and Wickham et al. (2006). Fecal contamination of fresh waters can arise through the deposition of feces by animals directly into waterways (Collins et al., 2007). Livestock grazing and dairies may increase the presence of fecal bacteria in the water (Maillard & Santos 2008; Wickham et al. 2006).

The application of RS and GIS techniques in deriving and integrating land use/land cover (LULC), water quality and hydrological information is becoming essential in scientific studies on water quality issues. Remote sensing data are now considered as crucial data input to the new generation of hydrological and water quality models (Rumman, Lin, & J. Li, 2005). Remote Sensing has been used primarily for extraction of land use / land cover to correlate with the occurrence of fecal coliform bacteria in ground and surface water (Maillard & Santos 2008; Steinman et al. 2007; Schoonover & Lockaby 2006; Kelsey et al. 2003).

Merot et al. (2004) defined a buffer zone as one which is applied to any kind of landscape feature that contributes to water pollution control by interrupting the flow of surface and subsurface waters. However, in the literature there are no clear trends on threshold distances that could be used for the near site expressions of the factors to describe the proximal influence on fecal contamination. Various studies investigating the occurrence of fecal coliform (and other contaminants) and its relationship to a range of factors used different buffer zones and distances (Merot et al. 2004; Wickham et al. 2006; S. Li et al. 2009; Swartz et al. 2003).

Hence, an understanding on the behavior of the fecal coliform and the local setting (e.g. topography, well characteristics, land cover, etc.) is therefore essential to determine the type of *pca* that influence the quality of groundwater of the study area.

Hierarchical (Cluster) Analysis, on the other hand, groups cases into classes based on similarities within a class and dissimilarities among different classes (Andrade et al., 2007). It is a multivariate statistical data reduction technique that can be used to group monitoring wells by aquifer water quality behavior (Suk & Lee 1999; Mathes & Rasmussen 2006). In the groundwater quality studies of Andrade et al. (2007) and Mathes and Rasmussen (2006), they demonstrated the use of various MSA techniques like Hierarchical Analysis and Principal Component Analysis to identify water quality factors and water quality group data with homogenous behaviors. Results of their study showed that MSA could provide improved estimates of contamination potential by augmenting observed contaminant concentrations with auxiliary information from other water quality parameters. Principal Component Analysis grouped variables that are most indicative of contamination potential while the Cluster Analysis of the principal components grouped monitoring wells with similar analyte behavior implying that monitoring wells are in the same geochemical zone.

3. A CASE STUDY IN THE CITY OF BUTUAN

3.1 The Study Area

The study area covers Butuan City which is located in the central portion of the province of Agusan del Norte in Northern Mindanao between 8°44’ and 9°03 latitude, and 125°26’ and 125°43’ longitude. The city is lying in the alluvial plain along the Lower Agusan River which directly empties into Butuan Bay.

Majority of the population of Butuan rely on groundwater as a source of potable drinking water. Urban growth has resulted rapid population increase and demand for drinking water but capacity for wastewater treatment are sorely lacking. City residents depend solely on septic systems for wastewater disposal. Though most of Butuan households are served by septic systems, these do not pass the standards imposed by the local government and numerous homes collect raw untreated sewage into pits. Furthermore, large proportion of Butuan’s land area is for agricultural purposes. Statistics from the Butuan City Agriculturist Office showed that backyard livestock and poultry production far exceeds commercial production as cited in the Socio-Economic and Demographic Profile (2000) of the city, which further showed that of the 199,889 heads of livestock and poultry in year 2000, 72.3% came from backyard production. Thus, groundwater system in the study area becomes highly susceptible to fecal contamination.

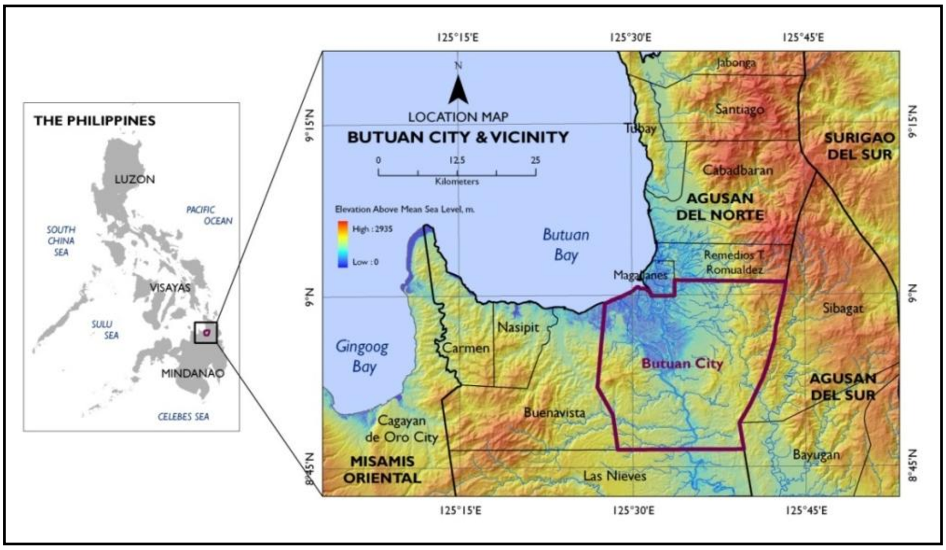


Figure 1 The study area: the city proper of Butuan

3.2 Well Sampling and Data Used

To determine the extent of fecal contamination in the study area, well water samples from 123 pump and dug wells were collected within the periods of April to June 2007. Fecal coliform densities were determined using Multiple Tube Fermentation Technique. Base on the Most Probable Number (MPN) of bacteria determined, wells were categorized into three groundwater quality indicators (GQI) such as "Negative" for negative detection of FC, "Positive: FC" for positive detection of FC, and "Positive: TC" for positive detection of total coliform (TC). The MPN or the fecal coliform densities were transformed further to approximate a normal distribution using the equation adopted form Kelsey et.al (2004):

$$\text{FC Density} = \log(\text{MPN} + 1) \qquad (1)$$

Well data used in this research includes the geographic locations of pump wells as well as important well characteristics such as depth, age, and the number of persons using the well. Also, this research utilized a land cover map and calibrated elevation model derived from ©ASTER 2005 data sets that include a 15-meter resolution satellite image and a 30-meter resolution DEM.

3.3 Methodology

Shown in Figure is the 0 (zero) diagram of the study that illustrates the main activities implemented to attain the objectives of this research.

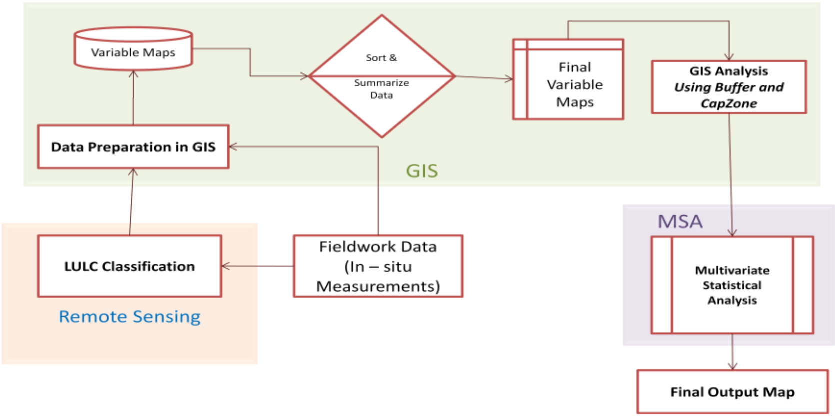
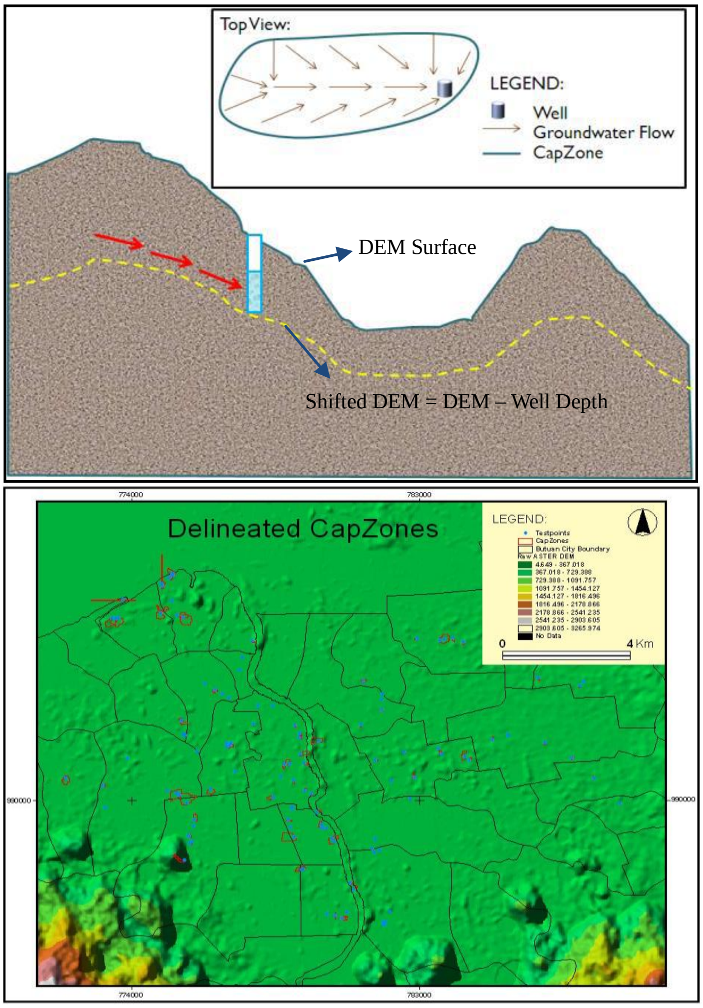


Figure 2 The methodological framework of the study

3.3.1 CapZone Delineation

In contrast to the conventional circular buffer zones used in various water quality studies, the approach of this research introduces the application of the concept of capture zone (CapZone) to best characterize the *pca* to groundwater fecal contamination. Using a calibrated digital elevation model (DEM), this study aims to demonstrate a GIS-based delineation of the CapZone that is consists of up-gradient areas that will drain to the pumping well. Each sampling point was regarded as the pour point of the *pca* for contamination to be able to determine the boundaries of the well's CapZone. A new surface should be derived for each well by subtracting the well depth to the calibrated DEM (illustrated in Figure 3). This new surface or the shifted DEM will be analyzed to satisfy two conditions for which a CapZone should be delineated: (1) *pca* must have elevations greater than the value of the well bottom elevation; and (2) flow directions, which were determined by tracing the flow paths (i.e. flow directions indicated by arrow graphics using ArcView® utility), must be pointing towards the well location.

For comparison, circular buffers of different radii (e.g. 740-m, 400-m, and 200-m) were created at the same sampling points where CapZones were previously delineated. Figure 4 shows the delineated CapZones in the study area.



At top is Figure 3 showing the CapZone Delineation Concept. At the bottom is Figure 4 showing the Delineated CapZones on sampled wells.

3.3.2 Geospatial Analysis and Variable Selection

A number of potential factor contributing to fecal contamination on groundwater exist in the study area including the well characteristics, land use/land cover, elevation and slope, nearby sampled septic tanks, and nearby commercial livestock raisers. Each of these represents a GIS layer or a factor map. Employing the two types of *pca*, a complete tabular datasets were derived by performing a series of geospatial analysis by which point locations of sampled wells were overlaid and geospatial relationships were determined and assigned to.

3.3.3 Multivariate Statistical Analysis

In order to identify significant factors that influence FC occurrence, a data reduction tool called Hierarchical Analysis (HA), was employed to group sampling points or *pca*s sharing similarities/dissimilarities in characteristics. Then, Multiple Linear Regression (MLR) models that will estimate FC density for every cluster were derived for the *pca* employing the CapZone and buffer method at three different radii. In order to have a basis for comparison of the models' relative performance, it is necessary that the two methods have common dataset/sample before running MLR. T-test was further employed to ascertain the significant difference between the linear regression models derived.

4. RESULTS AND DISCUSSIONS

4.1 CapZone Delineation

There were three kinds of Shifted DEM Analysis results; the "No Higher Elev" or surrounding areas with elevation values lesser than the well's bottom elevation, "No Flow" or surrounding areas of the wells where flow directions are not leading to the wells, and the "CapZone is Delineated" if surrounding areas have elevations greater than the wells' bottom elevation and flows are directing towards the well. Table 1 shows the tabulated results.

Table 1 Result of the Shifted DEM Analysis on wells and the frequency of wells according to groundwater quality indicator (GQI)

Analysis	Number of Wells	Percentage of Wells according to Groundwater Quality Indicator		
		Negative	Positive FC	Positive TC
No Higher Elev	28	22 78.6%	4 14.3%	2 7.1%
No Flow	5	5 100%		
CapZone is Delineated	90	43 47.8%	40 44.4%	7 7.8%

As shown in Table 1, out of 123 sampling points, 28 wells were found to be in an area with elevation lower than that of the wells' bottom elevations, 5 wells were found to be in an area where groundwater flow directions are not leading to the wells, thus, only a total of 90 CapZones were delineated. Of these 90 CapZones, 47.8% are negative in FC, 44.4% are positive in fecal coliform and the remaining 7.8% are those that are positive in total coliform (TC). It is also interesting to note that 100% of wells with flow directions not leading towards them were negative with FC. It can be inferred that the source of FC and TC on these wells may be very near to these wells or within 15 meters radial distance (DEM's resolution is 30 meters), that is, FC is directly infiltrated to groundwater.

4.2 CapZone versus Buffer

To identify significant factors among wells sharing commonalities/ dissimilarities of characteristics in each cluster, a data reduction tool called Hierarchical Analysis (HA) was employed. The HA resulted in 2 clusters for the *pca* employing the CapZone and buffer method. Derived linear regression models of FC density using the CapZone method generally yielded better R^2 values compared to the buffer method at three different radii as shown in Table 2.

This suggests that the concept of CapZones employed as the potential contributing area can better characterize the influence of land cover, elevation and slope to FC contamination compared to the buffer method.

Table 1 Comparison of the regression models' correlation coefficient (R^2) and Root Mean Squared Error (RMSE)

Cluster	Type of PCA	Model Performance	
		R^2	RMSE
1	CapZone	0.5	0.995
	740 Buffer	0.174	1.021
	CapZone	0.518	0.98
	400 Buffer	0.44	1.045
	CapZone	0.518	0.989
	200 Buffer	0.508	0.962
2	CapZone	0.688	0.667
	740 Buffer	No Significant Variables	
	CapZone	0.299	0.902
	400 Buffer	0.158	0.842
	CapZone	0.299	0.902
	200 Buffer	0.378	0.337

4.3 Significant Variables to FC Density

Well characteristics such as depth, bottom elevation, age, and the number of persons using the well were also found to be significant factors that can affect FC density. Well depth is negatively correlated to FC Density in both clusters 1 and 2. This could mean that as the depth or the number of persons using the well increases in the study area, FC density decreases. It is anticipated that the increased depth of well will increase the travel time of the coliforms, hence will decrease FC density that can contaminate the well. The significant influence of well depth was also established in other related studies. Well age is negatively correlated to FC Density in Cluster 1, one possible reason for this is that younger wells might be constructed in areas that were contaminated already by fecal coliform. The number of person using the well can be translated into the discharge rate of that well. The positive correlation between the numbers of persons using the well proved the usual perception that a large number of persons using the well will also increase the fecal coliform density. The relationship between this variable to FC density was explained with the findings of Abdel-lah & Shamrukh (2001) where high discharge rate of wells were found to increase the velocity of pore water and thus makes the travel of fecal coliform to reach pump wells faster. Hence, low fecal coliform count found on wells may be due to the low abstraction rate of water from well.

Built–up and Cropland areas are highly correlated to FC Density. However, these land cover classes have opposite effect or negative influence to the occurrence in FC bacteria. Built-up for example are positively correlated to FC density, while cropland is negatively correlated to FC density. This implies that an area dominant with built-up has high susceptibility to FC contamination while an area dominant with cropland are less prone to FC contamination. On the other hand, the minimum slope found within a CapZone was also a significant factor to FC contamination.

5. CONCLUSIONS

Upon implementing the maximization of RS-GIS techniques coupled with MSA, the following conclusions were reached: (1) remotely-sensed data is vital to infer groundwater flow directions and land cover data in relating the occurrence of fecal coliform on groundwater; (2) the concept of CapZones employed as the potential contributing area can better characterize the influence of land cover, elevation and slope to FC contamination compared to the buffer method; and (3) well characteristics such as depth, bottom elevation, age, and the number of persons using the well; land cover type like built- up and cropland; and slope are significant factors that can affect FC density on Butuan groundwater resource.

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