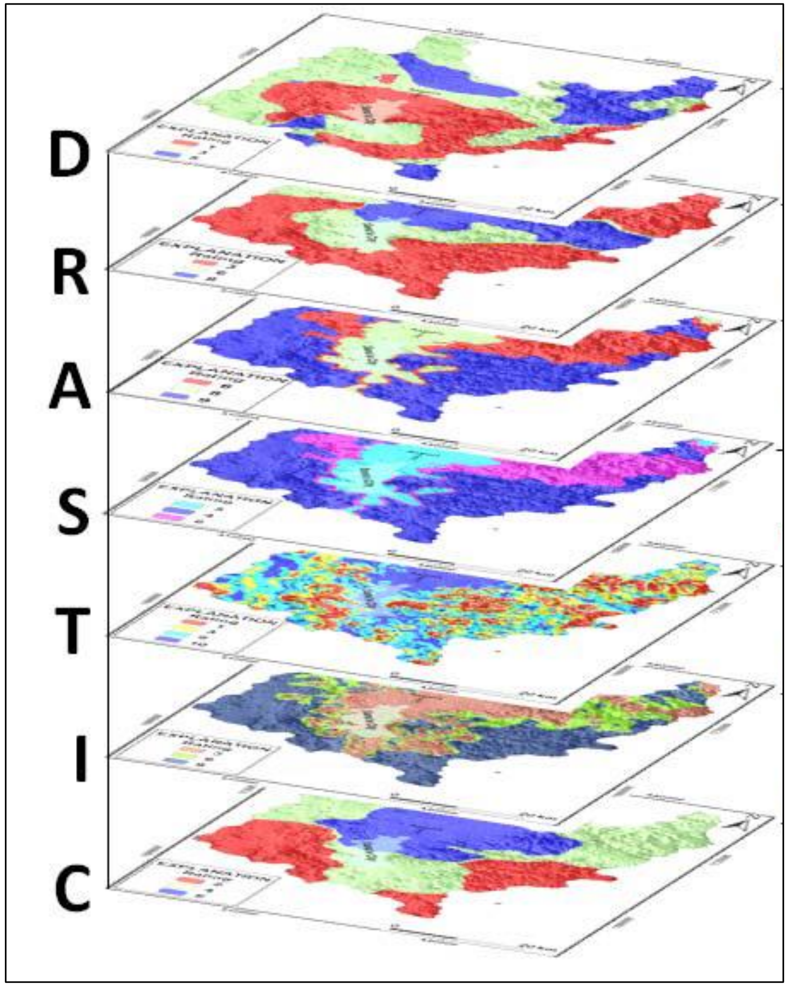
ASSESSMENT OF AQUIFER VULNERABILITY USING GIS-AIDED DRASTIC INDEX-OVERLAY METHOD AND MAPPING OF SALINE WATER INTRUSION USING ELECTRICAL RESISTIVITY SOUNDING METHOD: A CASE STUDY OF MASBATE CITY, MASBATE



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Outline of Presentation

- Background of the Study
- Study Area
- Methodology
- Results
- Conclusions

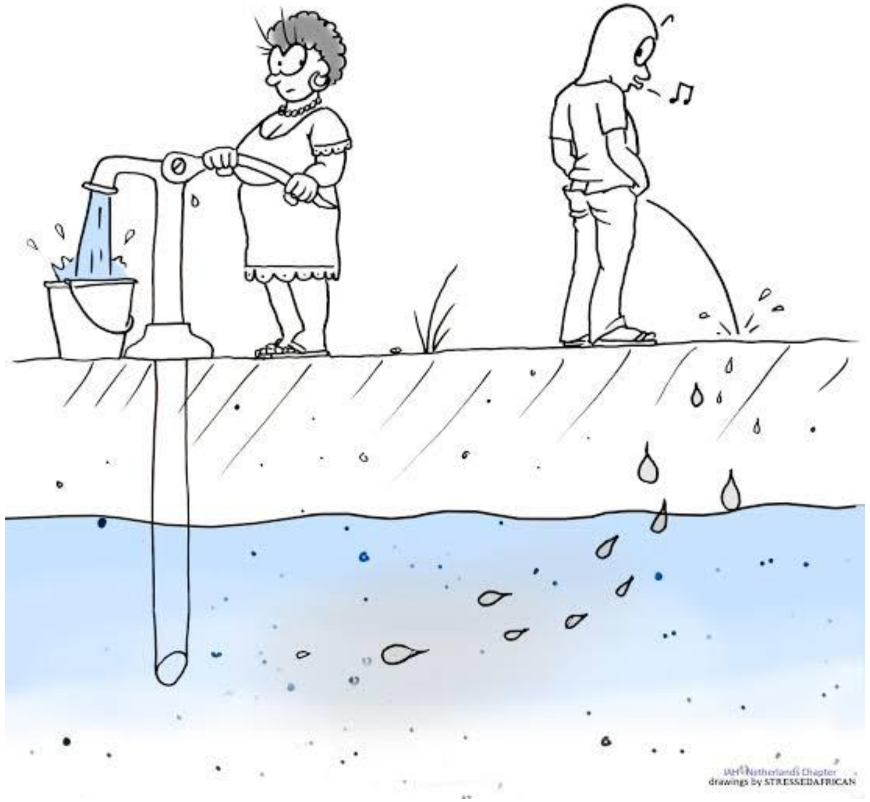
BACKGROUND OF THE STUDY

- Groundwater has been considered as an important source of water supply due its to its relatively low susceptibility to pollution in comparison to surface water (US EPA, 1985)

- The First Law of Groundwater Vulnerability:
  “All groundwater is vulnerable to contamination”

- The Second Law of Groundwater Vulnerability:
  “Uncertainty is inherent”

- The goal of Groundwater vulnerability mapping is to define the *spatial distribution*, *extent* and *degree of severity* of groundwater contamination susceptibility



BACKGROUND OF THE STUDY

- **Groundwater vulnerability to contamination** was defined as the tendency or likelihood for contaminants to reach a specified position in the groundwater system after introduction at some location above the uppermost aquifer (National Research Council,1993)

- Groundwater vulnerability is of two types:

Intrinsic vulnerability **-** focuses on the inherent geologic, hydrologic and hydrogeologic features of the natural environment and irrespective of the nature of the contaminant

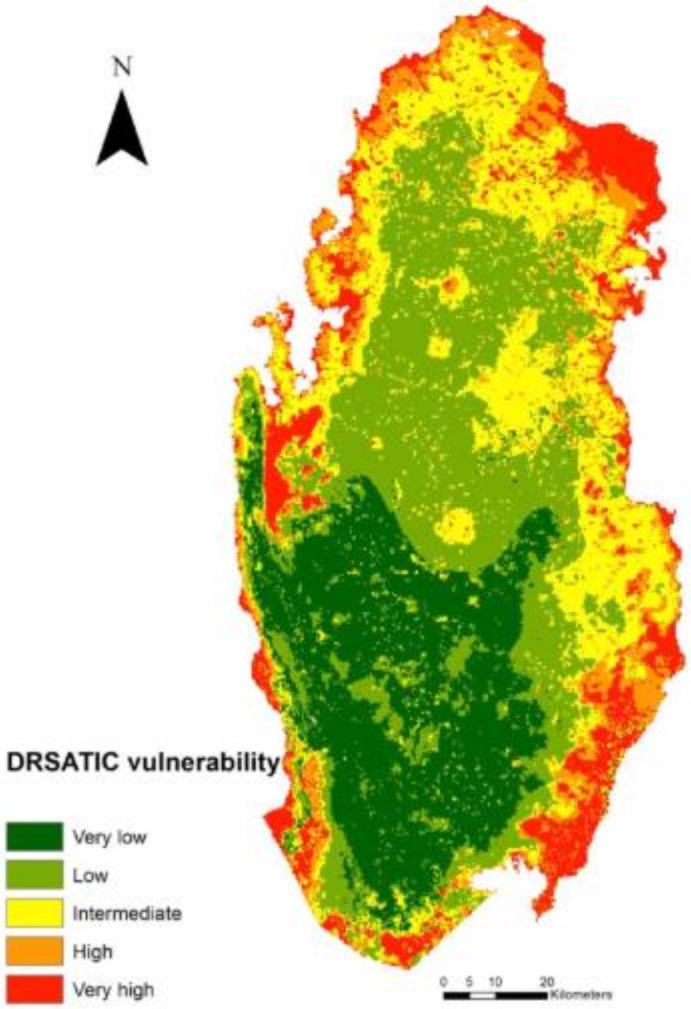
Specific vulnerability – incorporates the nature and spatial distribution of a specific contaminant

BACKGROUND OF THE STUDY

Rule 19.4 of Chapter 3, Section 19 of the Republic Act No. 9275 or the **Philippine Clean Water Act of 2004** that the Department of the Environment and Natural Resources (DENR), through the Mines and Geosciences Bureau (MGB), in coordination with the National Water Resources Board (NWRB), shall publish a national baseline groundwater vulnerability map that will reflect the different degrees of groundwater vulnerability to serve as guide in the protection of groundwater from contamination.

BACKGROUND OF THE STUDY

- Groundwater vulnerability maps are beneficial to:
  - Planners
  - Developers
  - Local stakeholders
- who can utilize them for:
  - Policy analysis and development
  - Program management to allocate resources
  - Informing land use decisions
  - Education and awareness creation
- Vulnerability mapping does not replace site-specific investigations, but can act as a *guide* to *emphasize highly vulnerable areas* for management practices



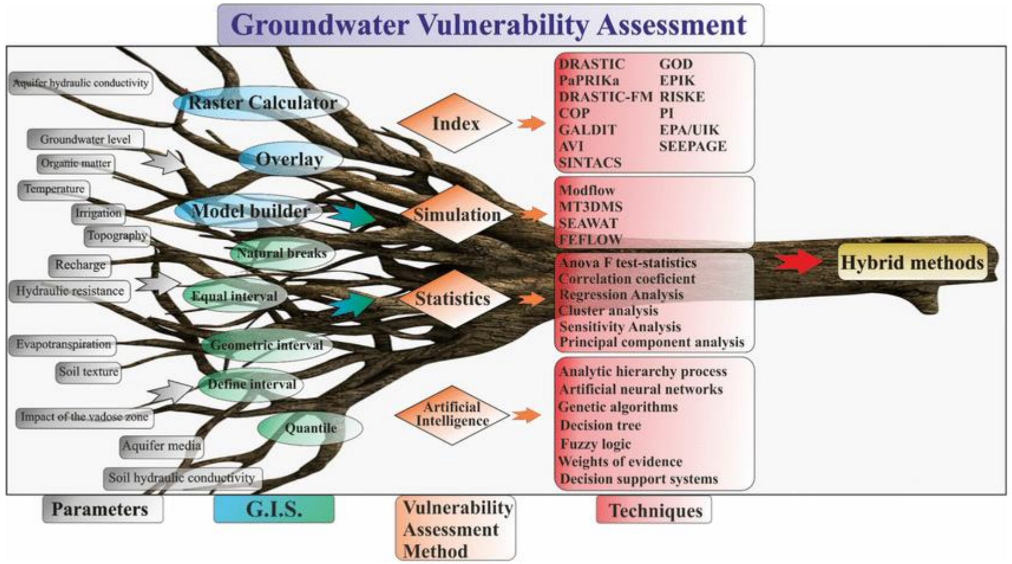
BACKGROUND OF THE STUDY

➢ Groundwater vulnerability can be assessed by three main methods:

1. Process Based Method – use simulation models (from simple to complex 3D simulation model) to simulate contaminant transport

2. Statistical Method– use statistics to determine associations between spatial variables and actual occurrence of pollutants in the groundwater

3. Overlay and Index Method– combine factors controlling the movement of pollutants from the ground surface into the saturated zone resulting in vulnerability indices at different locations



BACKGROUND OF THE STUDY

- The Overlay-Index methods are most widely applied approaches to groundwater vulnerability analysis
- Known to be suitable for regional studies since it requires easily accessible/available data (topography, soil, geology and depth to groundwater table)
- The most widely applied techniques of overlay-index method are as follows:
  - GOD (Foster 1987)
  - **DRASTIC (Aller et al. 1987)**
  - SEEPAGE (Moore and John 1990)
  - AVI (Van Stempvoort et al. 1993)
  - SINTACS (Civita 1994)
  - ISIS (Civita and De Regibus 1995)
  - EPIK (Doerfliger and Zwahlen 1997)
  - The Germen method (Von Hoyer and Sofner 1998)
  - IRISH (Daly and Drew 1990)

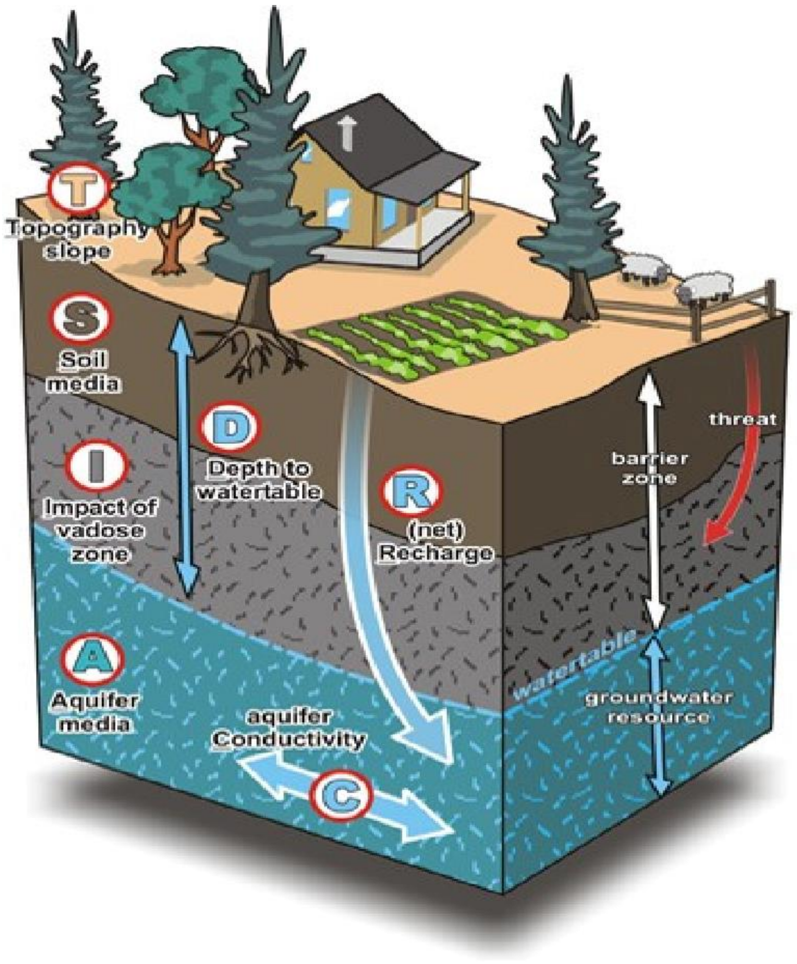
BACKGROUND OF THE STUDY

- DRASTIC is an example of index model designed to produce vulnerability scores for different locations by combining several thematic layers

- The DRASTIC method was developed by the US Environment Protection Agency (USEPA) in 1987 (Aller et al).

- The DRASTIC model is the widely accepted and used groundwater vulnerability analysis method*

- The acronym DRASTIC stands for the seven parameters used in the model which are: **D**epth to water, **R**echarge, **A**quifer media, **S**oil media, **T**opography, **I**mpact of vadose zone and hydraulic **C**onductivity



* Worrall and Kolpin 2004; Babiker et al. 2005)

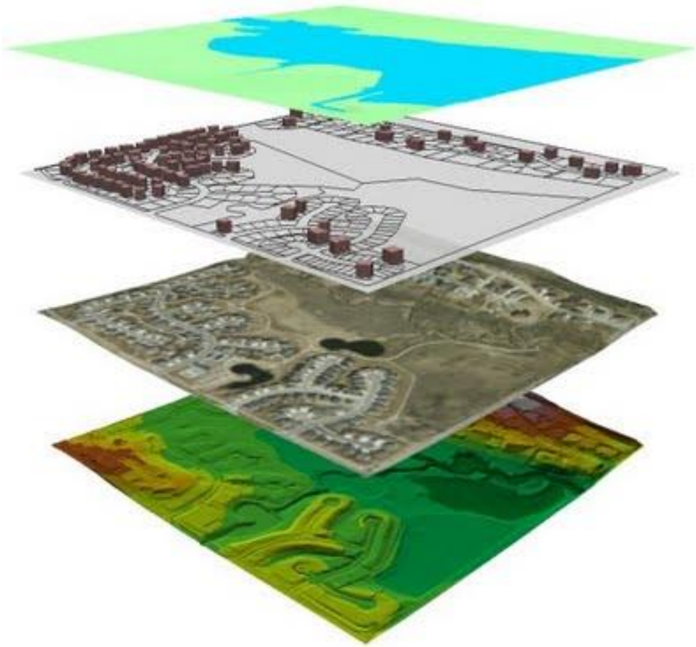
BACKGROUND OF THE STUDY

The **DRASTIC** method assumes that:

- any contaminant is introduced at the ground surface;
- the contaminant is flushed into the groundwater by precipitation;
- the contaminant has the mobility of water;
- the areas evaluated using 0.4 km^2 or larger

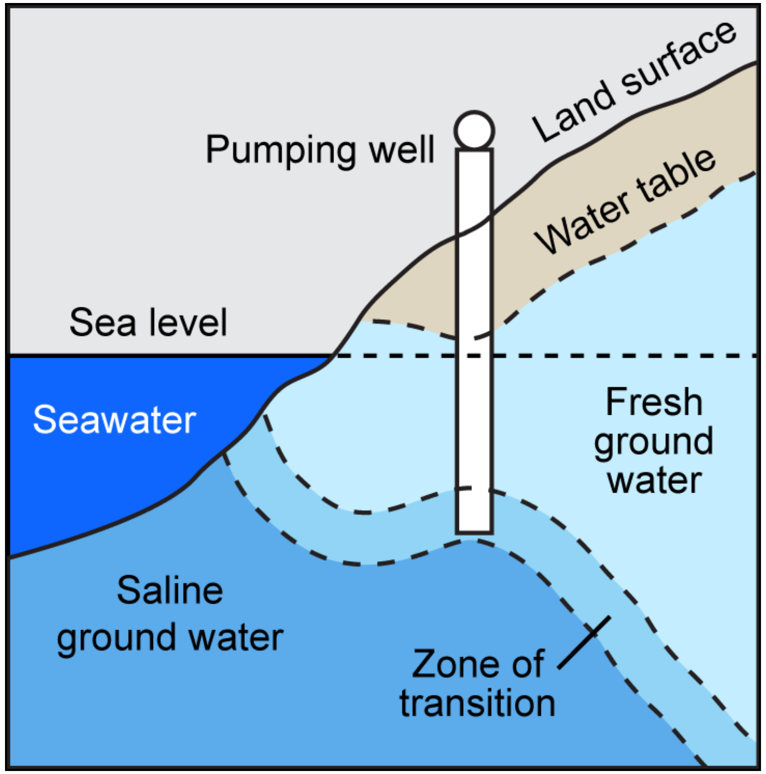
➢ Recently, Geographic Information System (GIS) techniques have been widely used in aquifer vulnerability mapping.

➢ In GIS systems, all types of geographically-referenced data are spatially registered so that multiple themes of data can be compared and analyzed together.



BACKGROUND OF THE STUDY

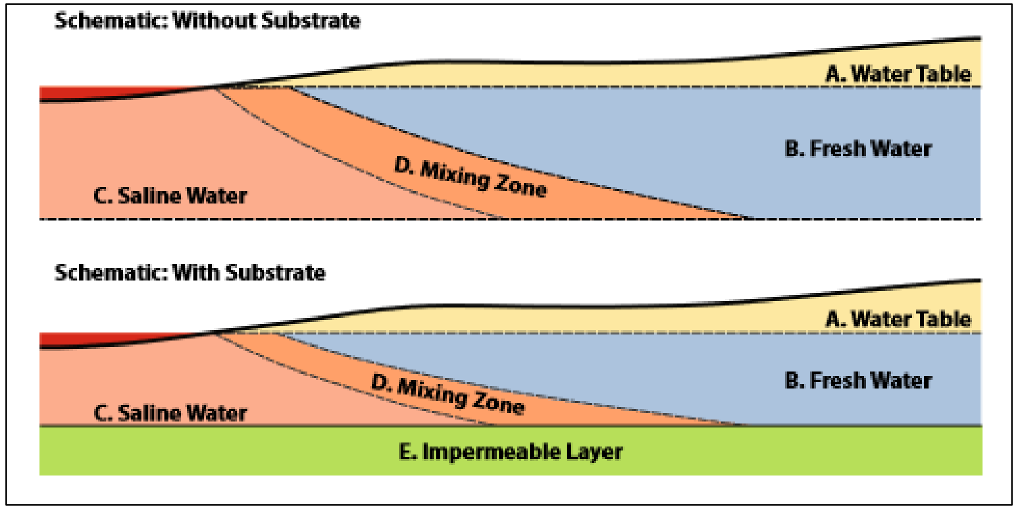
- Another type of groundwater contamination that was dealt in this study is the contamination of freshwater bodies by **saltwater intrusion**
- Freshwater in coastal aquifers is particularly vulnerable to degradation due to its close proximity to seawater and the significant water demand associated in coastal areas.



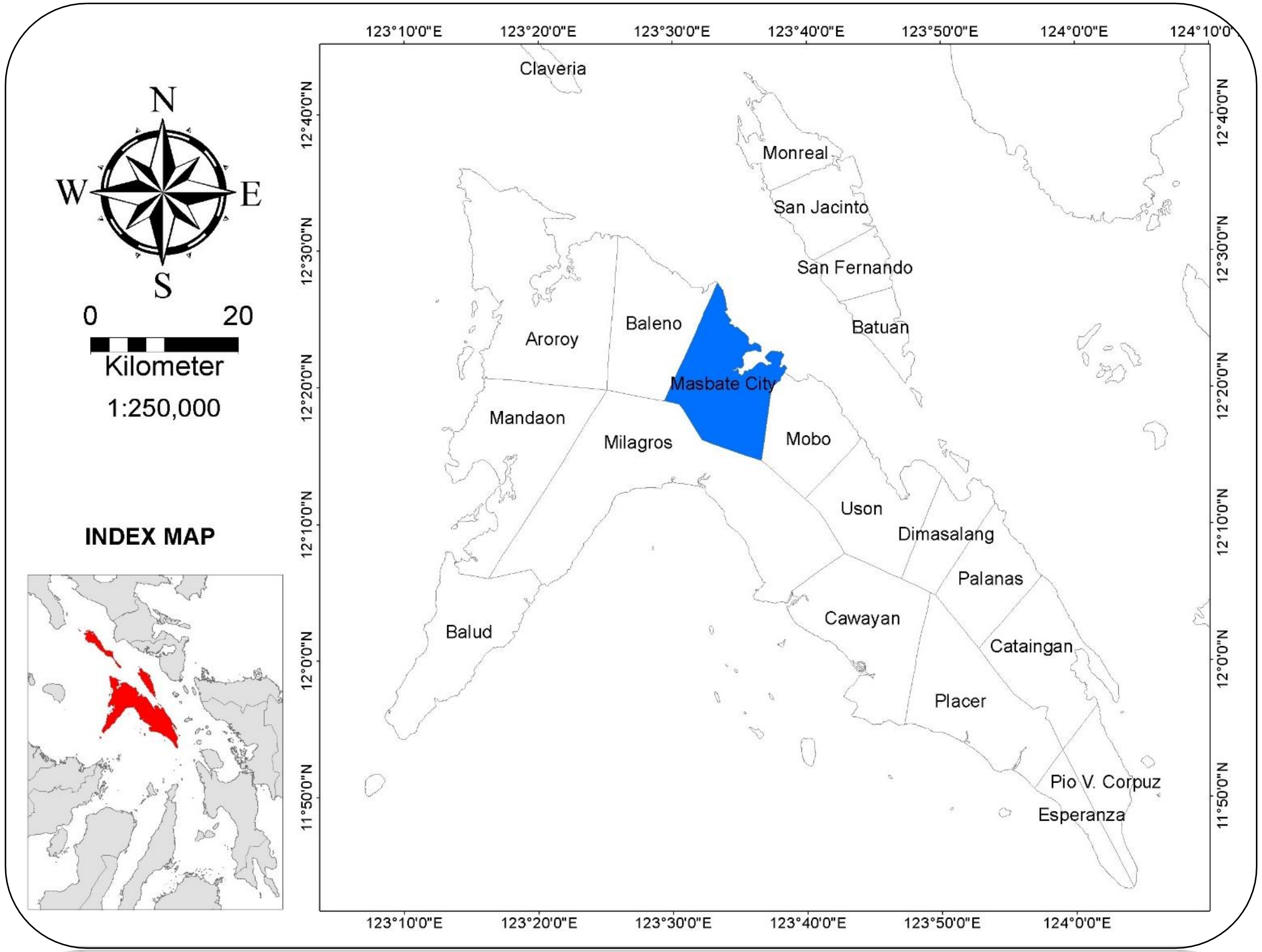
BACKGROUND OF THE STUDY

The characteristic wedge shape of the seawater interface is the combined result of many factors:

- the density contrasts between fresh and seawaters,
- the distribution of hydraulic properties,
- flow-through of groundwater toward the ocean,
- rain- fall recharge and
- the distribution of groundwater abstraction and recharge.



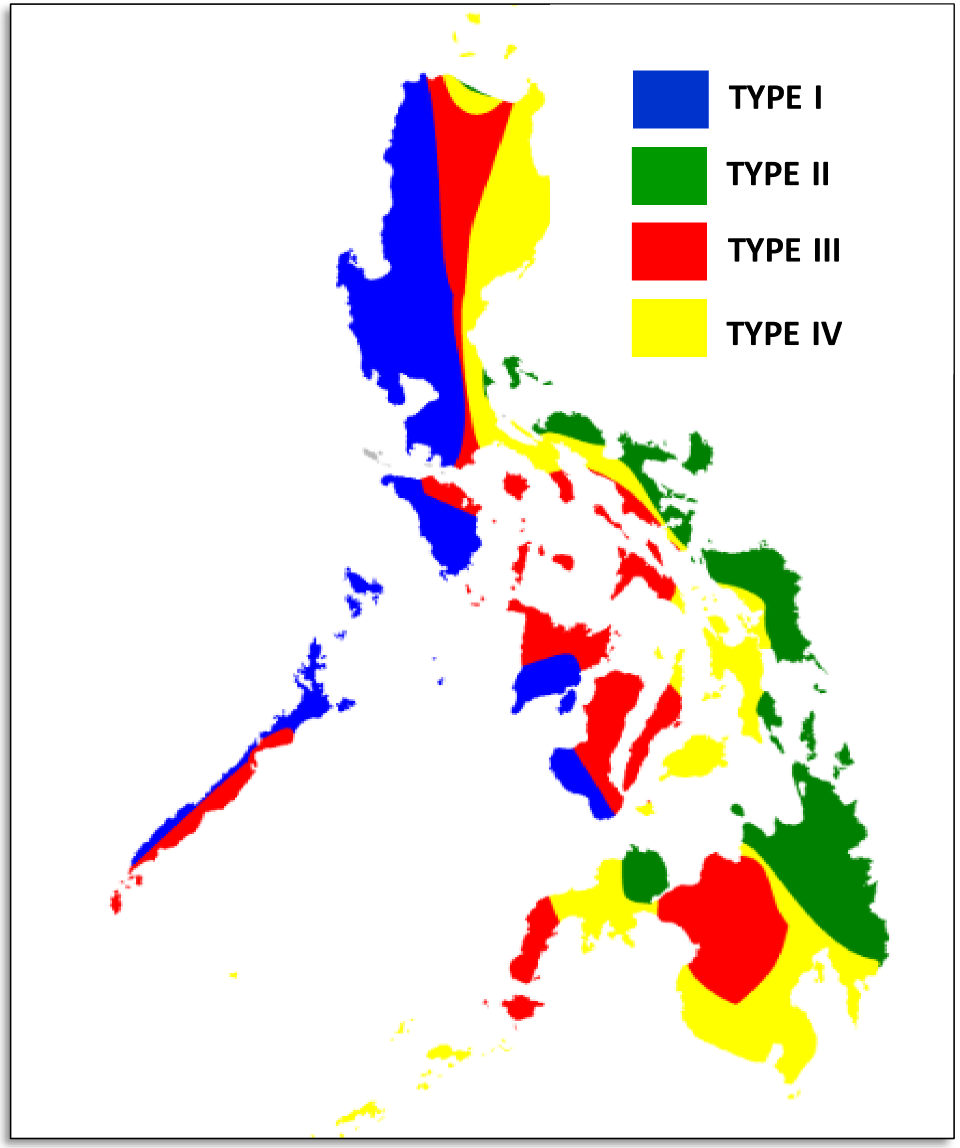
STUDY AREA



Basic Profile:

- 12˚ 21’ 00”N 123˚ 34’ 00” E
- 30 Barangays (10 urban)
- 188.60 km^2
- Population: 95,389 (PSA,2015)

STUDY AREA



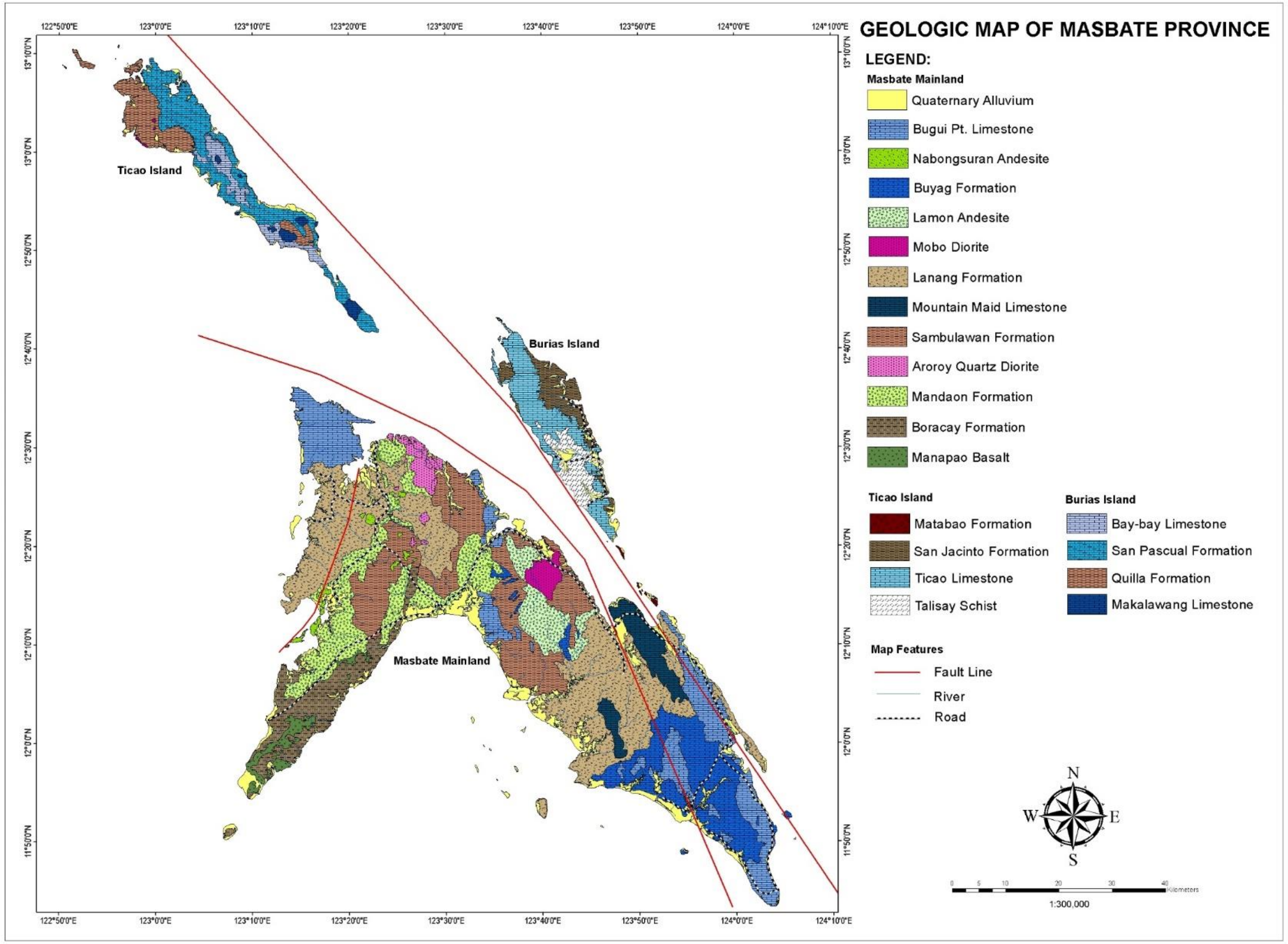
Climate:

Type III under the Modified Corona's Classification
(has no very pronounced maximum rain period with a dry season lasting only from one to three months)*

2050 mm annual average precipitation *

* PAGASA

STUDY AREA



*Geology of the Philippines, Second Edition (MGB, 2010)
** Geology of Masbate Province (Matos and Baybayon, 1985)

Geology

Regional Setting:

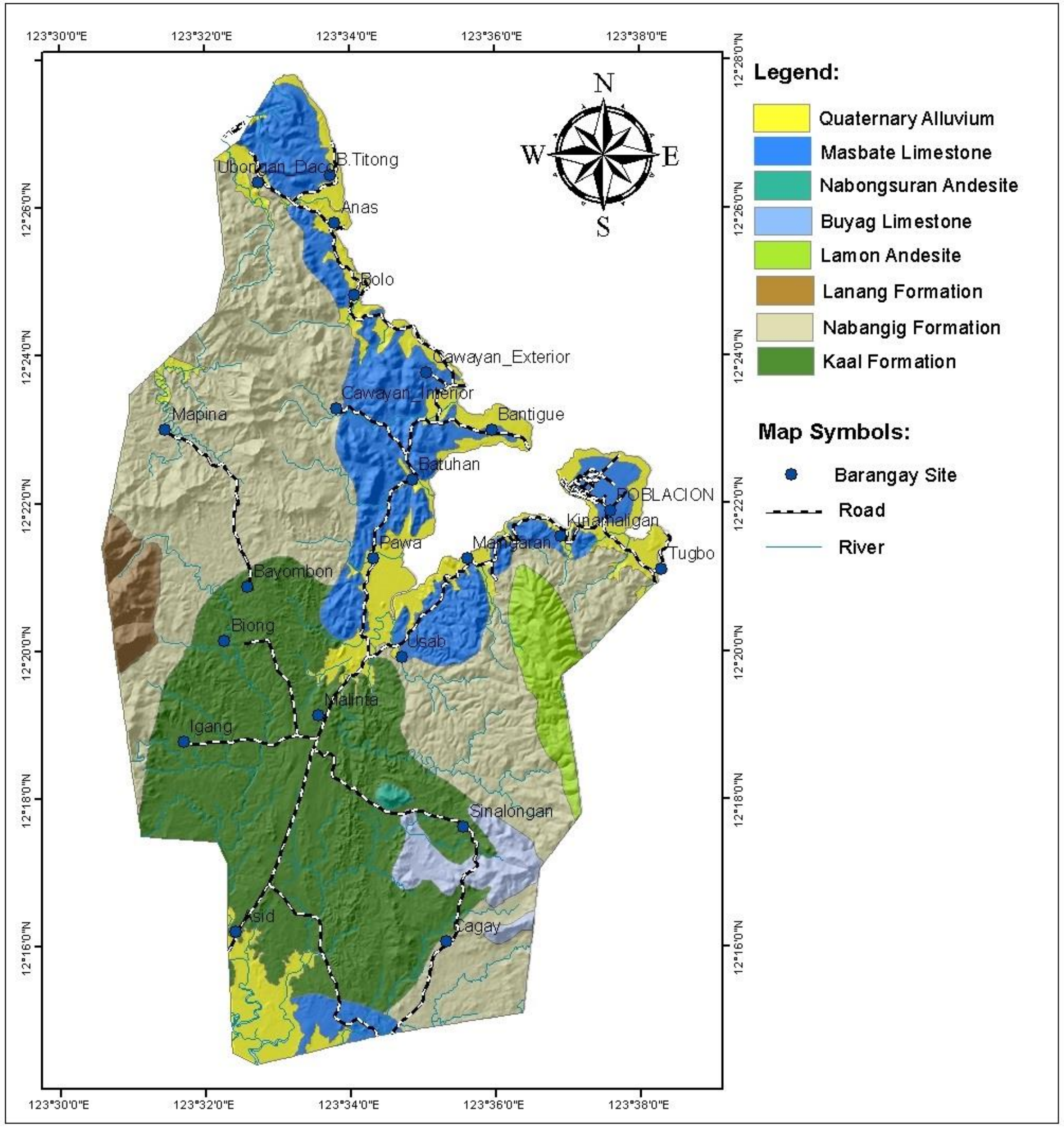
The oldest rock units: pre-Cretaceous Mt. **Manapao Basalt** and **Calumpang Formation** exposed together as a window representing deep marine volcanic flows and the corresponding pelagic capping of an ophiolitic basement*

The youngest rock unit: **Pleistocene Masbate Limestone***

The southern tip of the Island defines the northern edge of the Visayan Sea Basin**

The southwest limb constitutes a part of the Northeast Panay Physiographic Ridge **

STUDY AREA



Masbate Limestone
Age: Pleistocene
Lithology: massive limestone which is largely coralline to crystalline

Nabongsuran Andesite
Age: Pliocene
Lithology: andesitic plugs, stocks and flows with pyroclastics

Buyag Limestone
Age: Late Miocene – Early Pliocene
Lithology: clastic rocks that fine upwards from basal massive conglomerate grading to coarse calcareous sandstone

Lamon Andesite
Age: Middle Miocene
Lithology: fine-grained andesitic volcanic rocks

Lanang Formation
Age: Middle Miocene
Lithology: conglomerates composed of well consolidated, poorly sorted basalt and andesite clasts

Nabangig Formation
Age: Late Oligocene
Lithology: sequence of conglomerate, siltstone, limestone, wackes, mudstones and basalt breccia

Kaal Formation
Age: Eocene
Lithology: Mainly basalt with andesitic and dacitic facies

METHODOLOGY (DRASTIC Method)

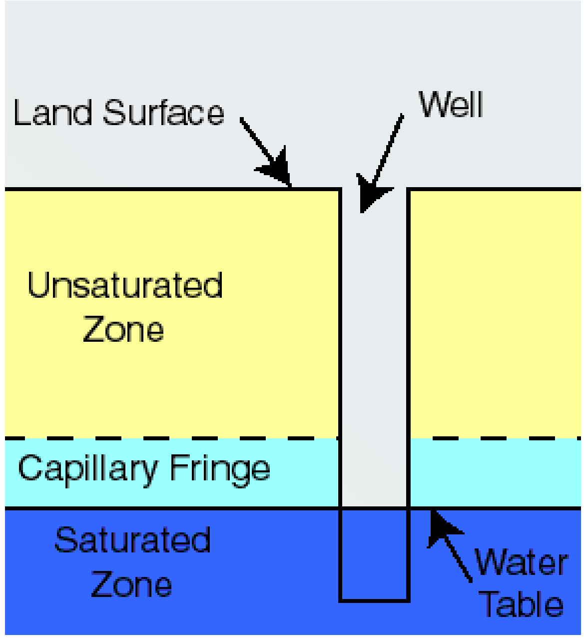
DATA ACQUSITION AND PROCESSING

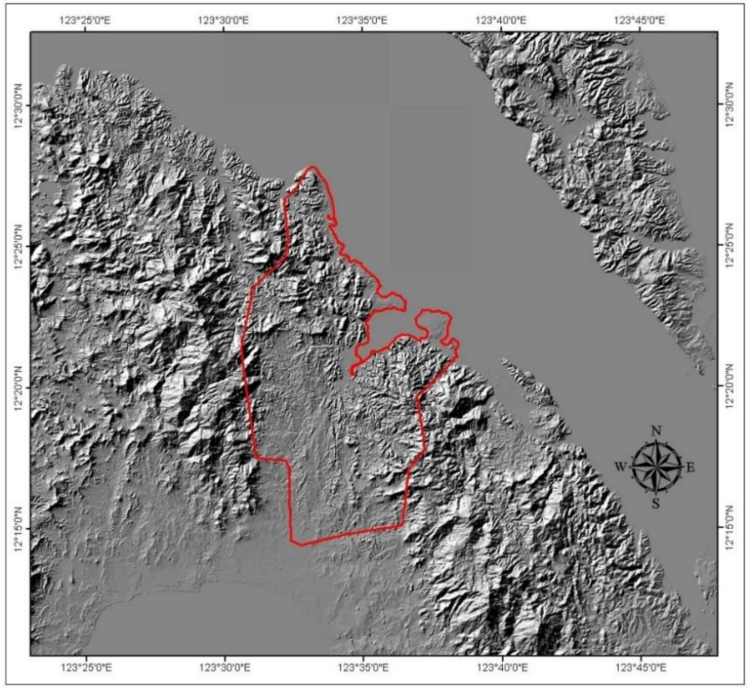
Data Type	Sources	Output Layer
Groundwater table level	In-situ water table measurement	Depth of Water **(D)**
Average annual rainfall	PAGASA	Recharge **(R)**
Geology	MGB	Aquifer Media **(A)**
Soil map	BSWM; PhilGIS	Soil Media **(S)**
Digital Elevation Model (DEM)	NAMRIA (Lidar)	Topography **(T)**
Geologic and Borehole data	MGB	Impact of Vadose Zone **(I)**
Hydraulic Conductivity	MGB, Hydrogeology book	Hydraulic Conductivity **(C)**

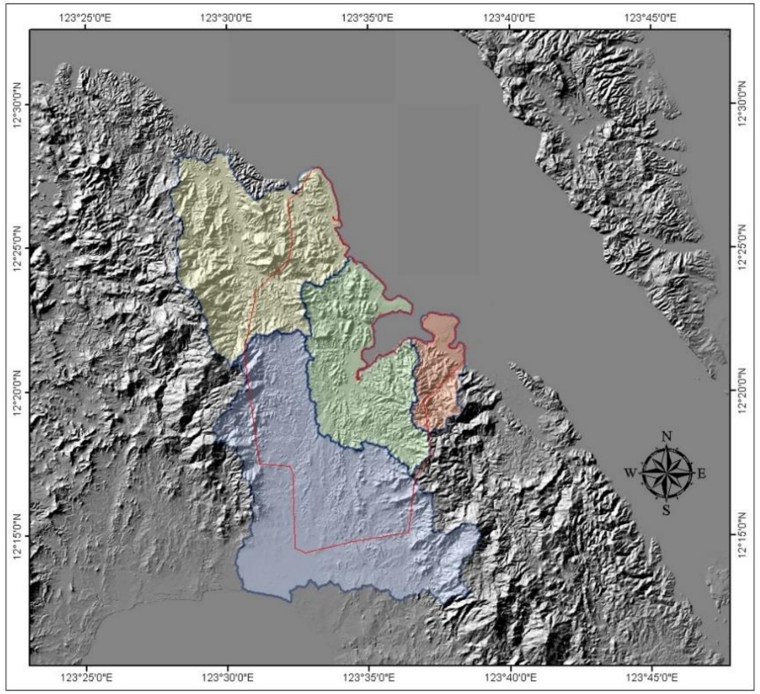
DATA ACQUSITION AND PROCESSING

Depth to Water Table **(D)**

- It determines the depth of material through which a contaminant must travel before reaching the aquifer.
- The depth to water is the distance from the ground surface to the water table.





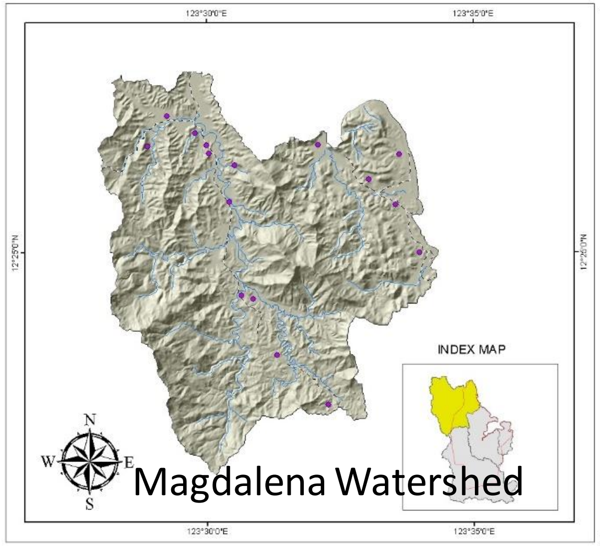


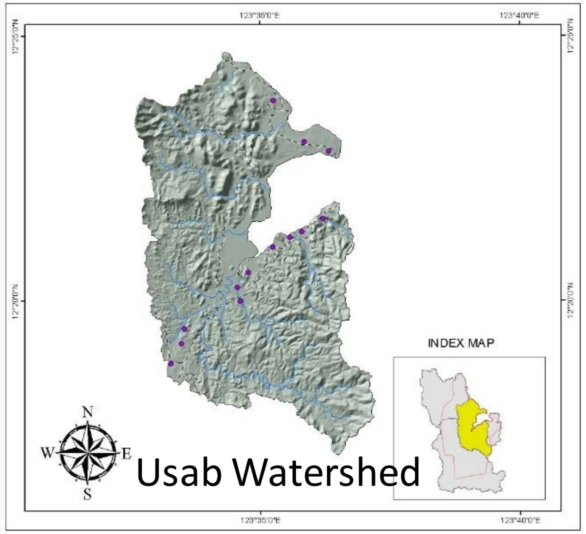
DATA ACQUSITION AND PROCESSING

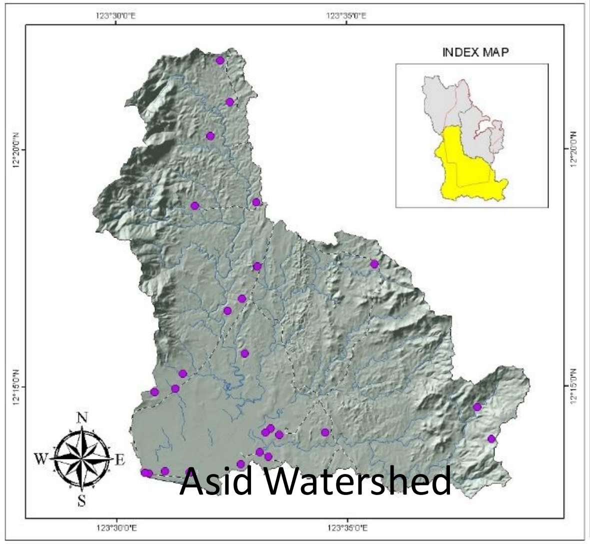
Depth to Water Table **(D)**

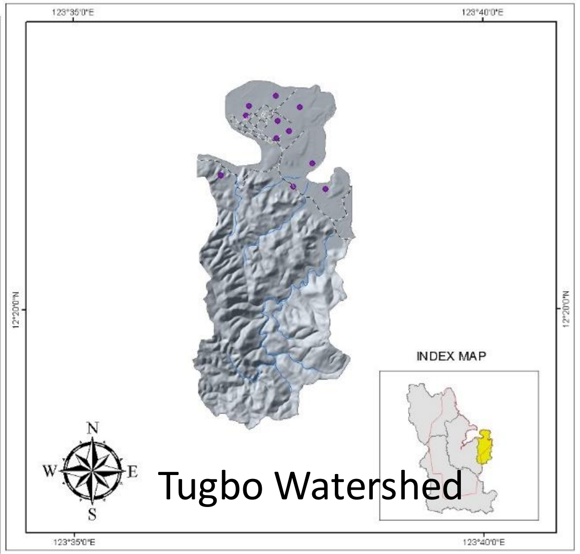
Groundwater table measurement

Drastic Parameters	Range	Rating	Weight
Depth to Water Table (D)	0 – 1.5 m 1.6- 4.5 m 4.6 – 9.0 m 9.1 – 15.0 m 15.1 – 23.0 m 23.1 – 30.0 m > 30.0 m	10 9 7 5 3 2 1	**5**



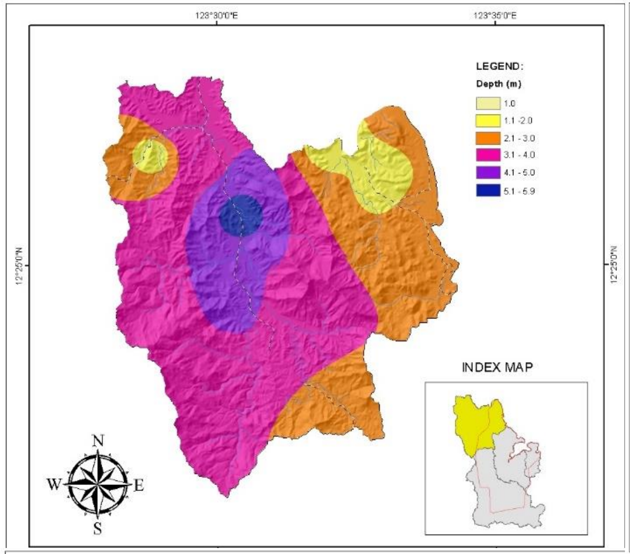


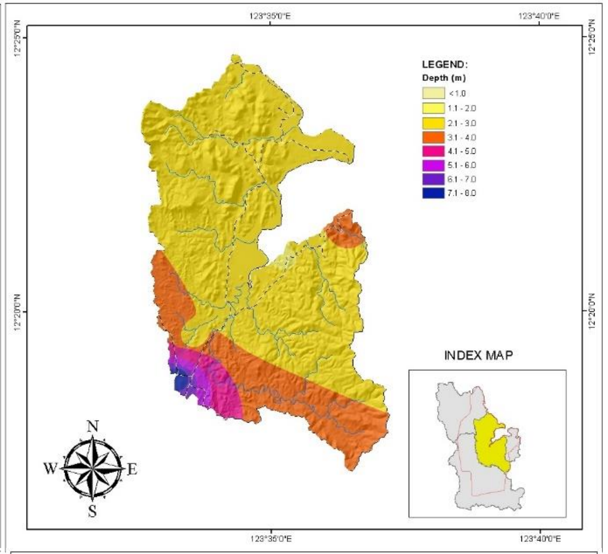


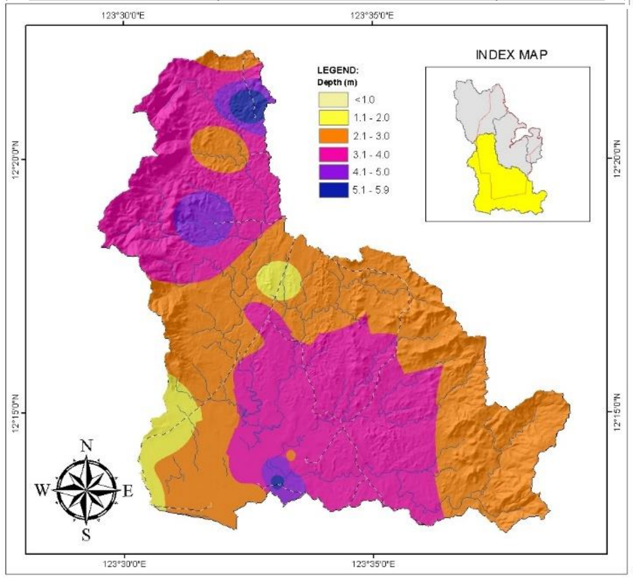


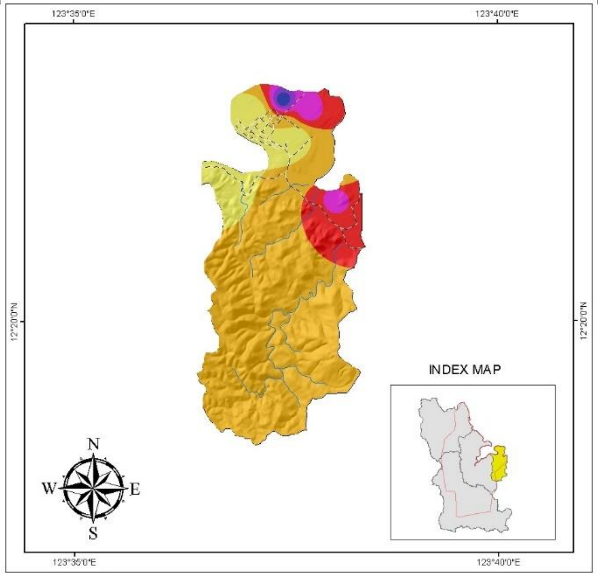
DATA ACQUSITION AND PROCESSING

Depth to Water Table **(D)**









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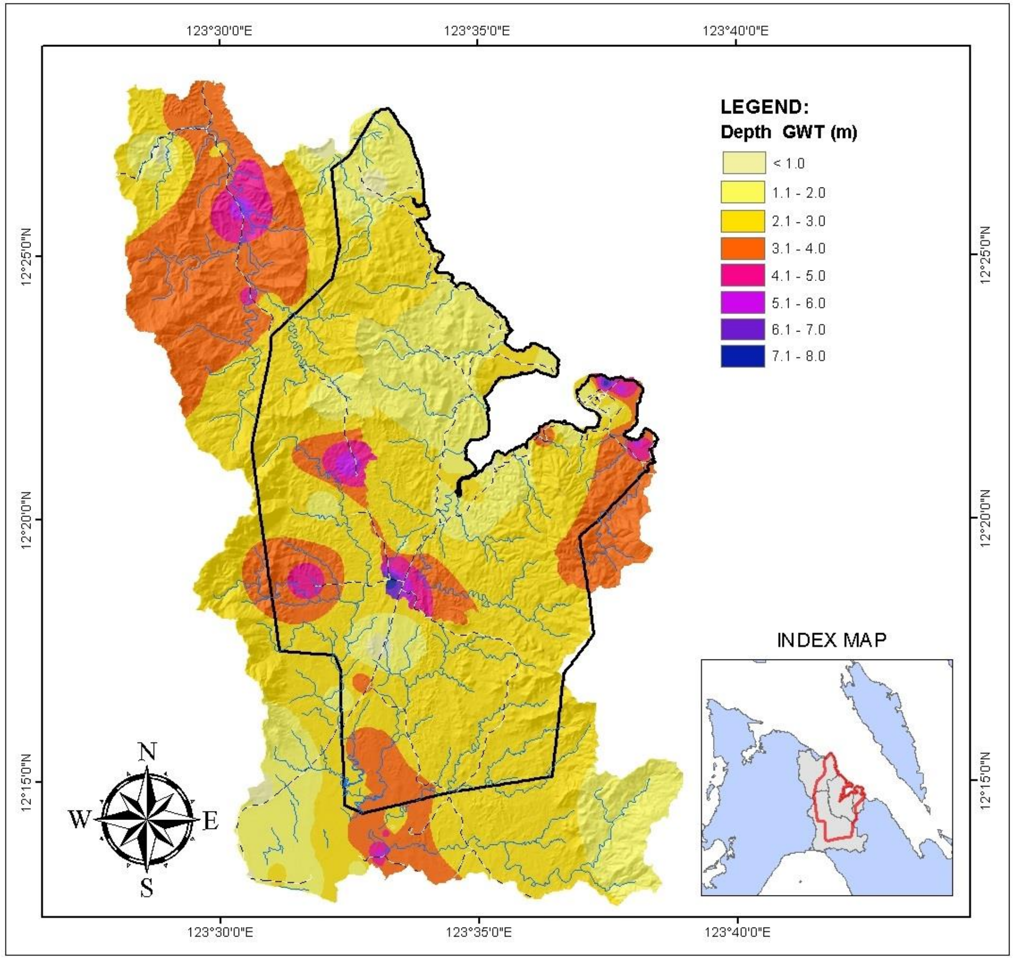
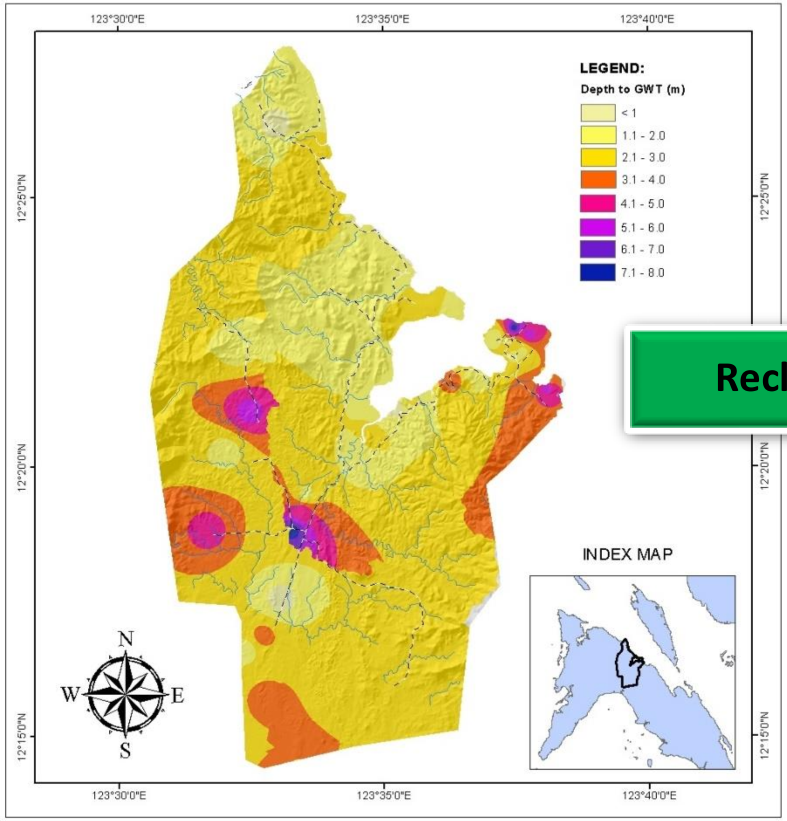


DATA ACQUSITION AND PROCESSING

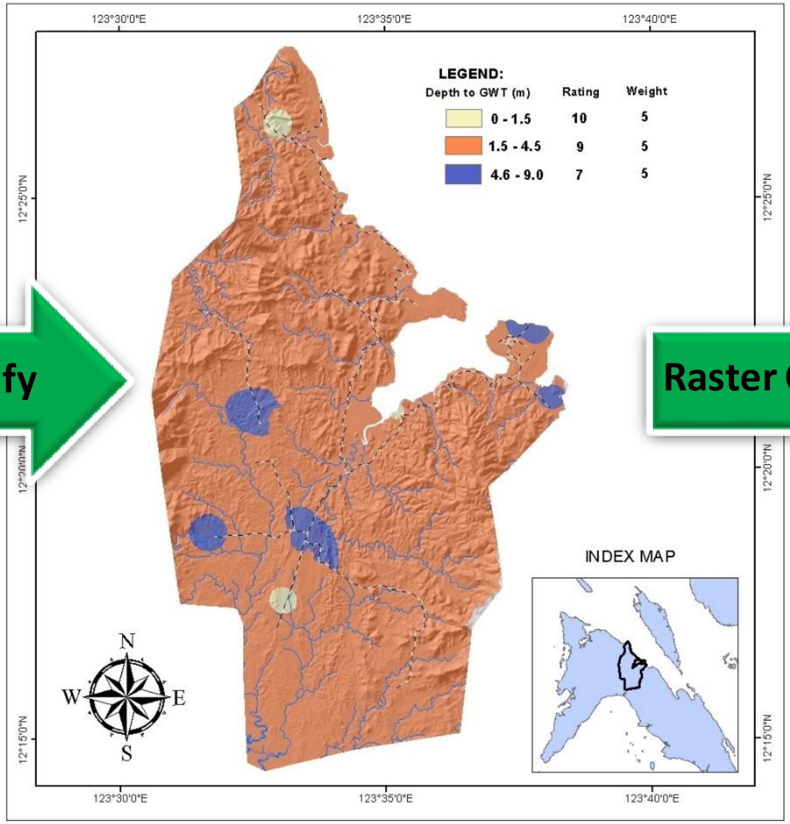
Depth to Water Table **(D)**

RANGE	RATING	WEIGHT	VULNERABILITY_IN
0 -1.5	10	5	50
1.6 -4.5	9	5	45
4.5 - 9	7	5	35



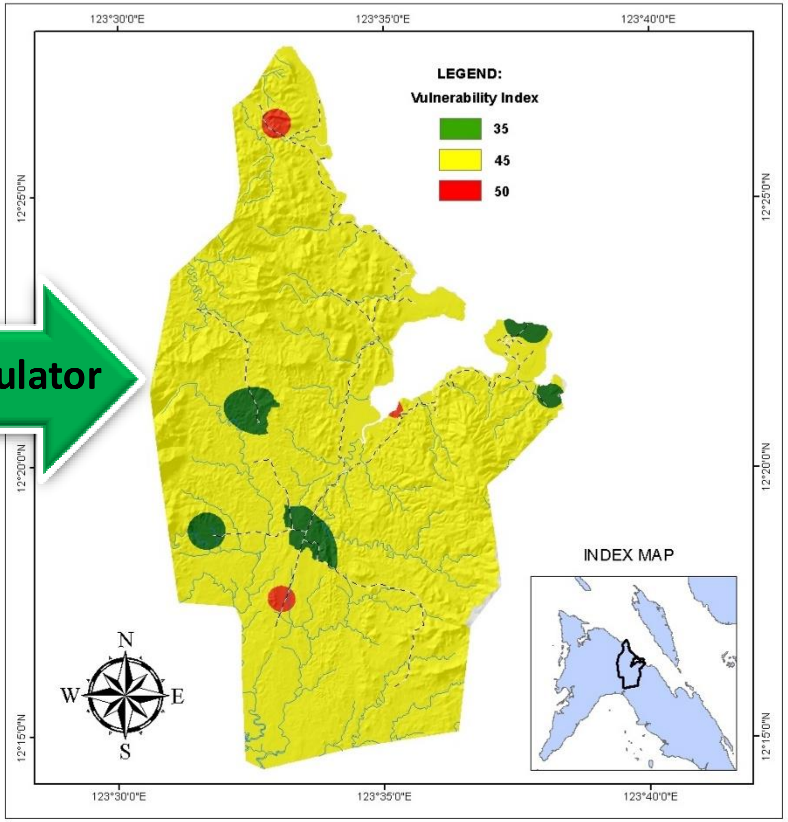
Depth to Water Table Map

Reclassify



Drastic Parameters	Range	Rating	Weight
Depth to Water Table (D)	0 – 1.5 m	10	5
	1.6- 4.5 m	9	
	4.6 – 9.0 m	7	
	9.1 – 15.0 m	5	
	15.1 – 23.0 m	3	
	23.1 – 30.0 m	2	
	> 30.0 m	1	

Raster Calculator



Depth to Water Table Vulnerability Index Map

DATA ACQUSITION AND PROCESSING

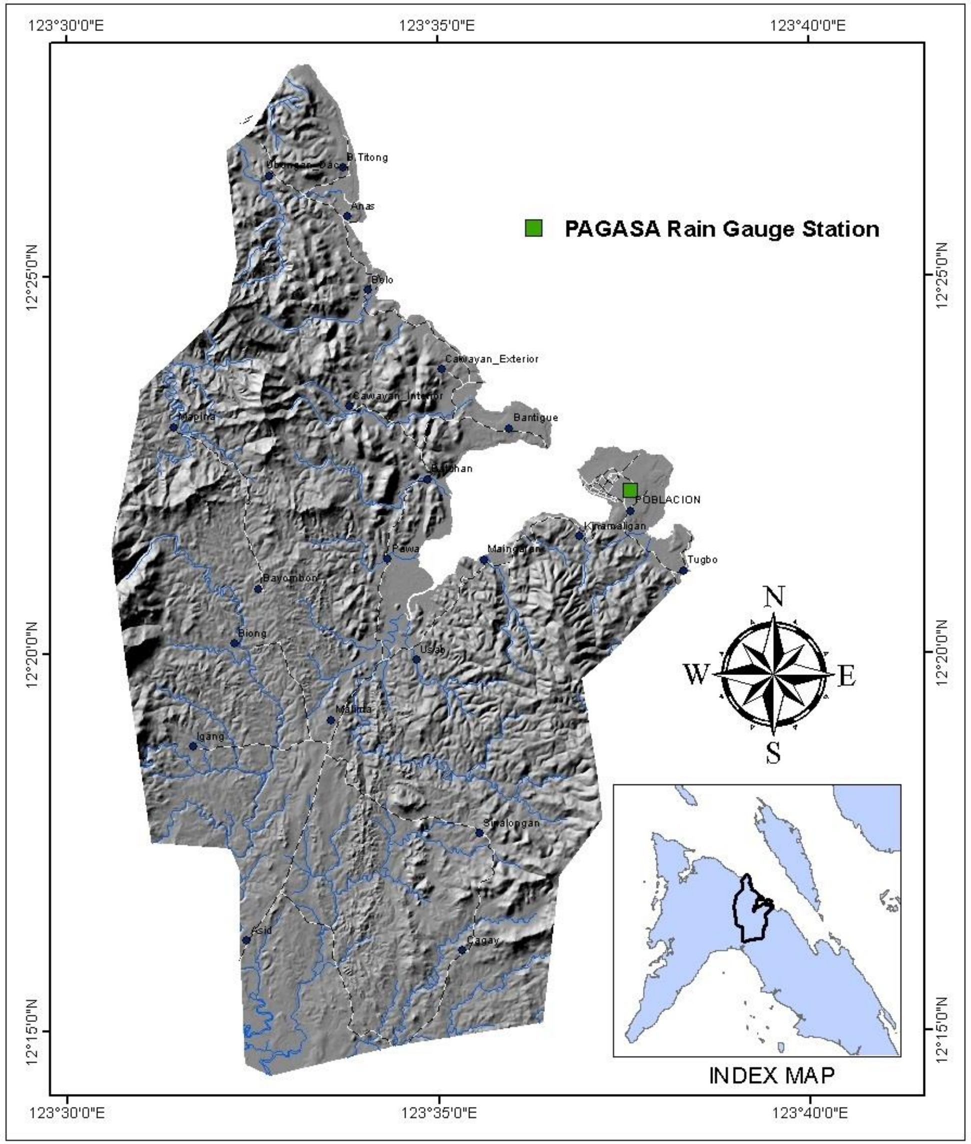
Recharge **(R)**

Drastic Parameters	Range	Rating	Weight
Recharge (R)	0 - 50 mm 51 – 100 mm 101 – 180 mm 181 – 254 mm > 254 mm	1 3 6 8 9	**4**

- Represents the amount of water which penetrates the ground surface and reaches the water table
- Recharge is the principal vehicle for leaching and transporting contaminants to the water table

Month	Rainfall (mm)	Mean Temp (°C)
January	169.3	26.9
February	101.8	27.2
March	86.9	28.1
April	54.1	29.3
May	118	29.8
June	155.7	29.5
July	227	28.9
August	178.1	28.9
September	212.6	28.8
October	233	28.6
November	254.9	28.1
December	258.9	27.9

Source: PAGASA (1981 -2010)



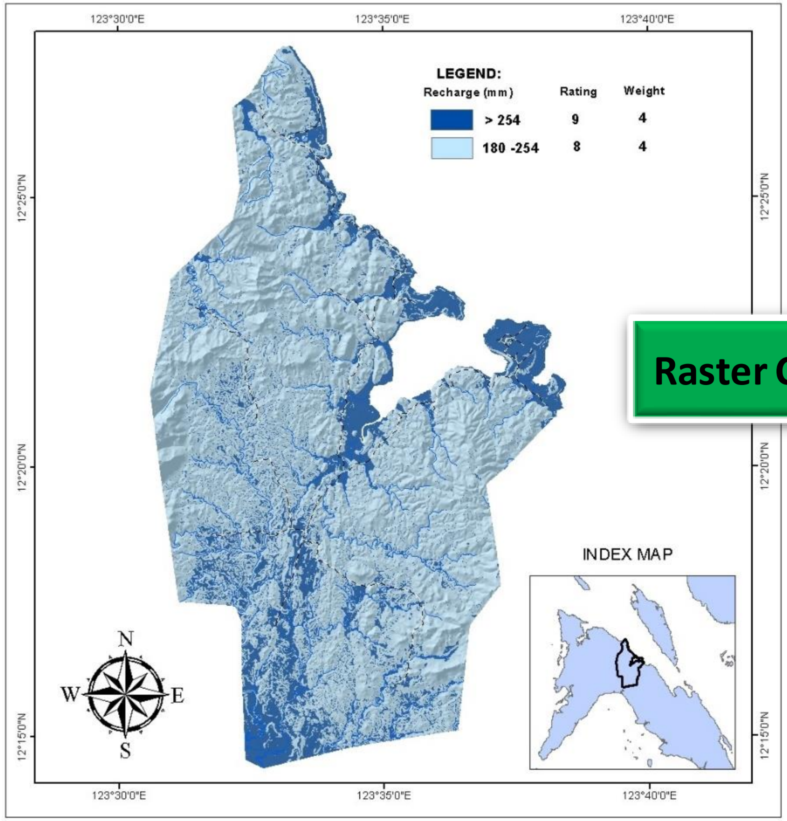
Estimated Annual Recharge in Masbate City is ≈ 200 mm

DATA ACQUSITION AND PROCESSING

Recharge **(R)**

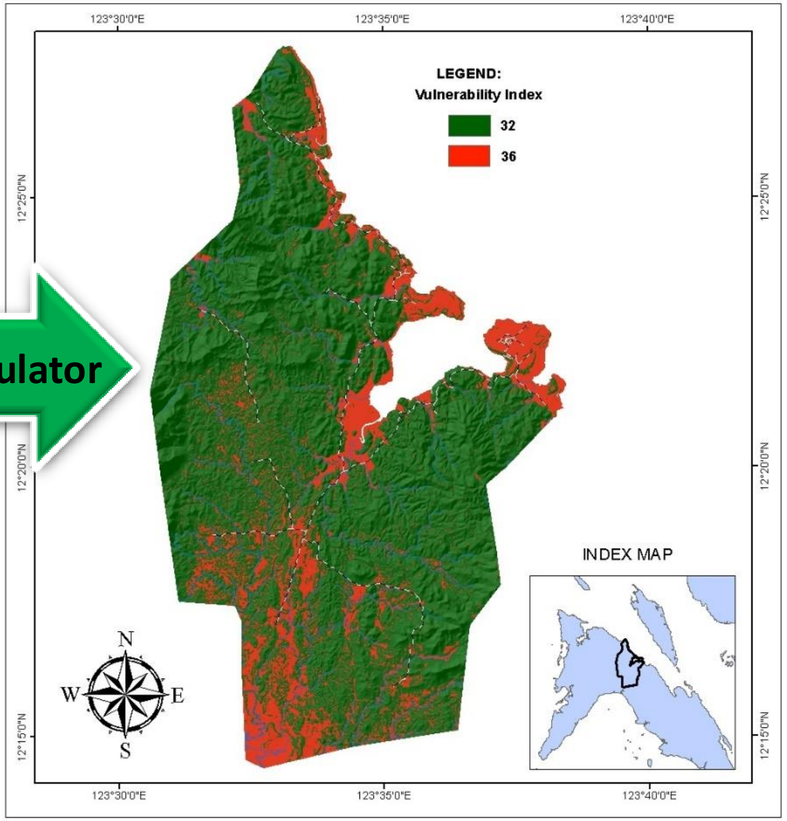
RANGE	RATING	WEIGHT	VULNERABILITY_IN
> 254	9	4	36
180 -254	8	4	32

- at much steeper slopes, runoff is increased and recharge is reduced due to the decrease in surface storage capacity. **Flat (0% - 2%) to gently sloping terrain (2%-6%)** therefore have **higher recharge rate** due to occurrence of higher ponding pressure and thicker surface flow layer



Recharge Map

Raster Calculator

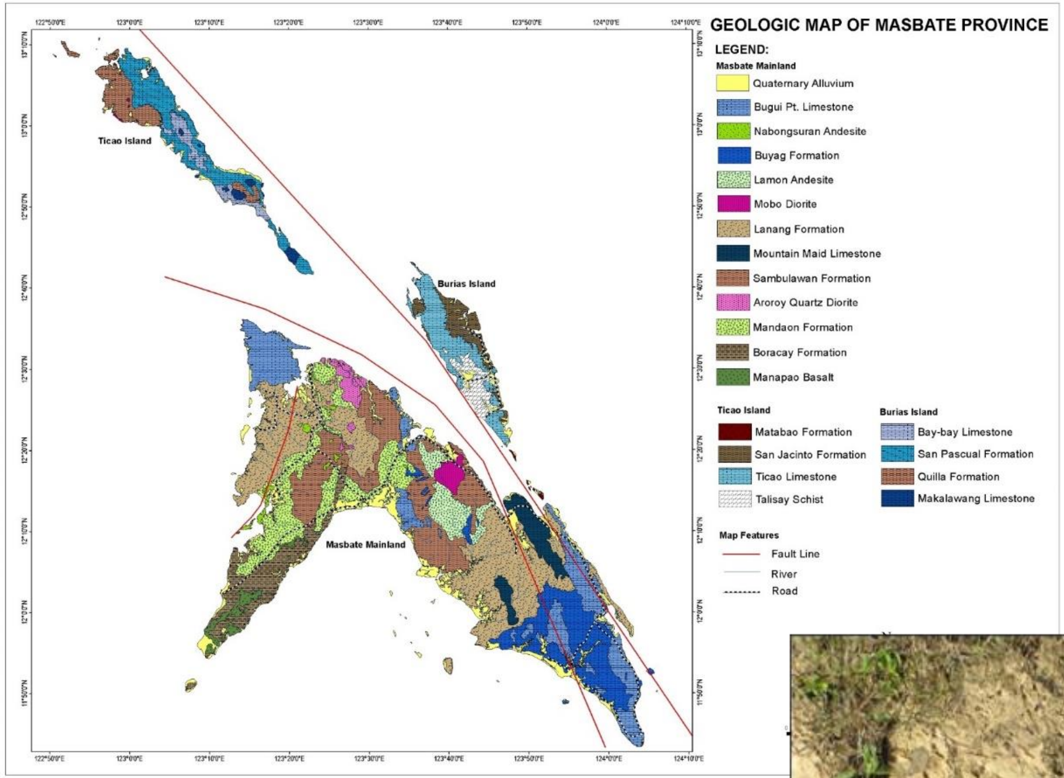


Recharge Vulnerability Index Map

Drastic Parameters	Range	Rating	Weight
Recharge (R)	0 - 50 mm 51 – 100 mm 101 – 180 mm 181 – 254 mm > 254 mm	1 3 6 8 9	**4**

DATA ACQUSITION AND PROCESSING

Aquifer **(A)**



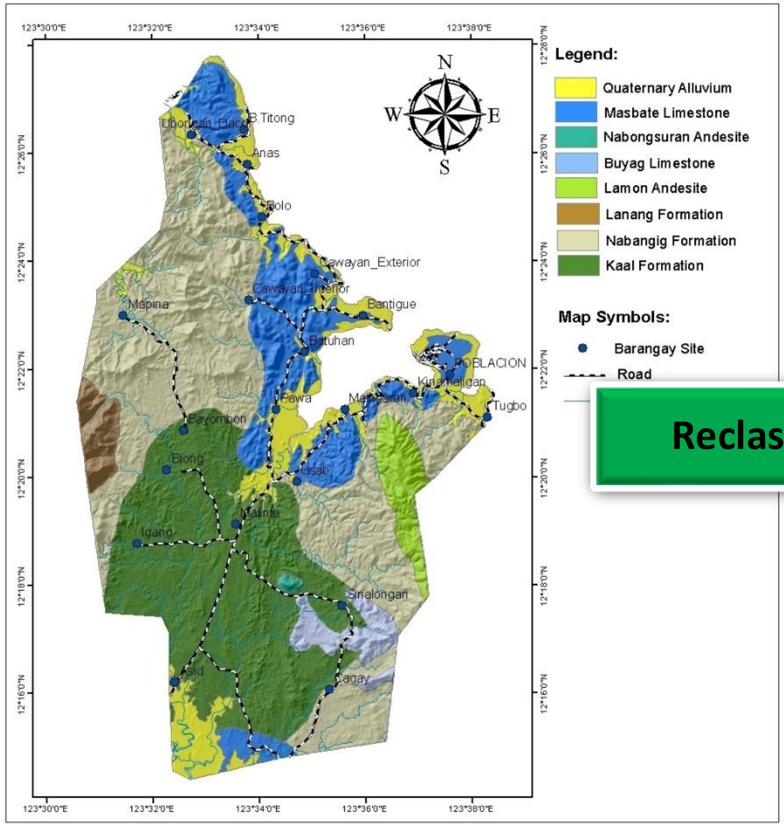
Drastic Parameters	Range	Rating	Weight
Aquifer (A)	Massive Shale	2	
	Metamorphic/Igneous	3	
	Weathered Metamorphic/Igneous	3	
	Thin Bedded Sandstone/Limestone	4	**3**
	Shale Sequence	6	
	Massive Sandstone	6	
	Massive Limestone	6	
	Sand and Gravel	8	
	Basalt	8	
	Karst Limestone	10	

- Refers to the saturated zone material properties , which controls pollutant attenuation processes

DATA ACQUSITION AND PROCESSING

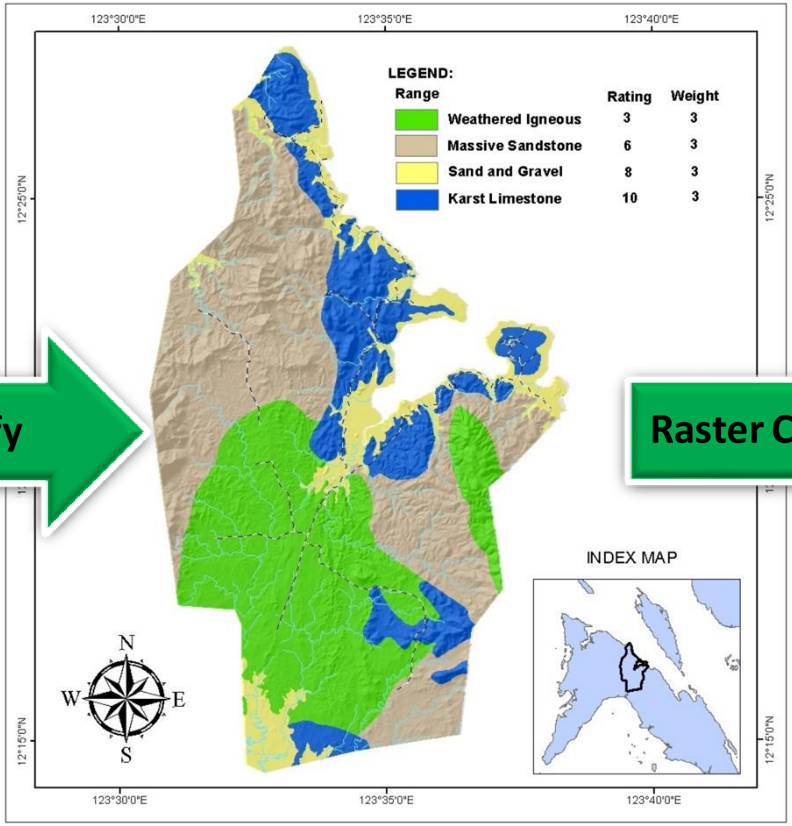
Aquifer **(A)**

RANGE	RATING	WEIGHT	VULNERABILITY_IN
Weathered Igneous	3	3	9
Karst Limesone	10	3	30
Sand and Gravel	8	3	24
Massive Sandstone	6	3	18



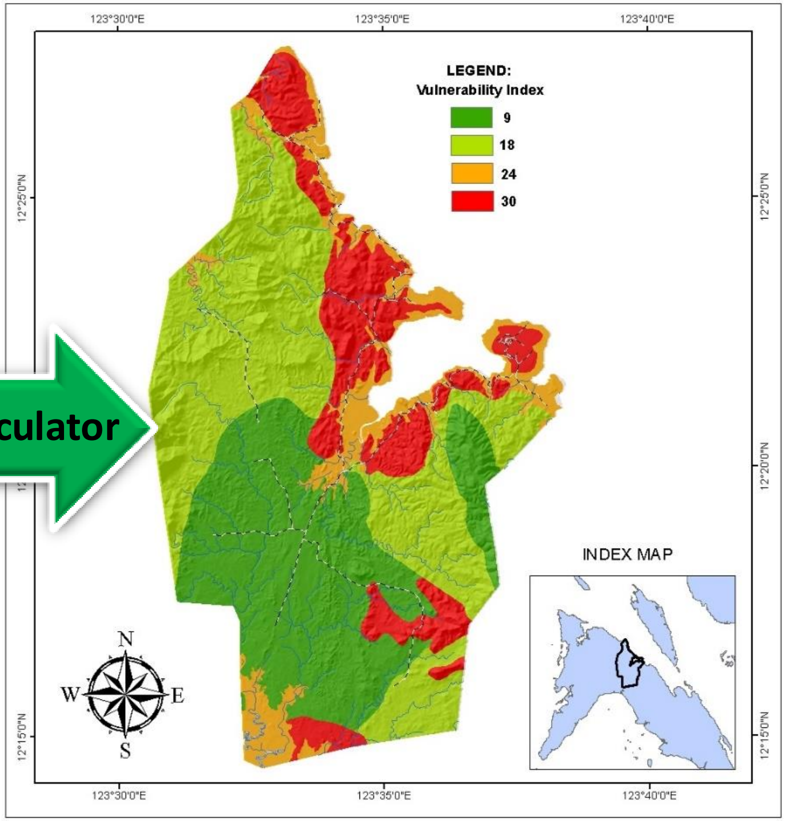
GeologicMap

Reclassify



Aquifer Map

Raster Calculator



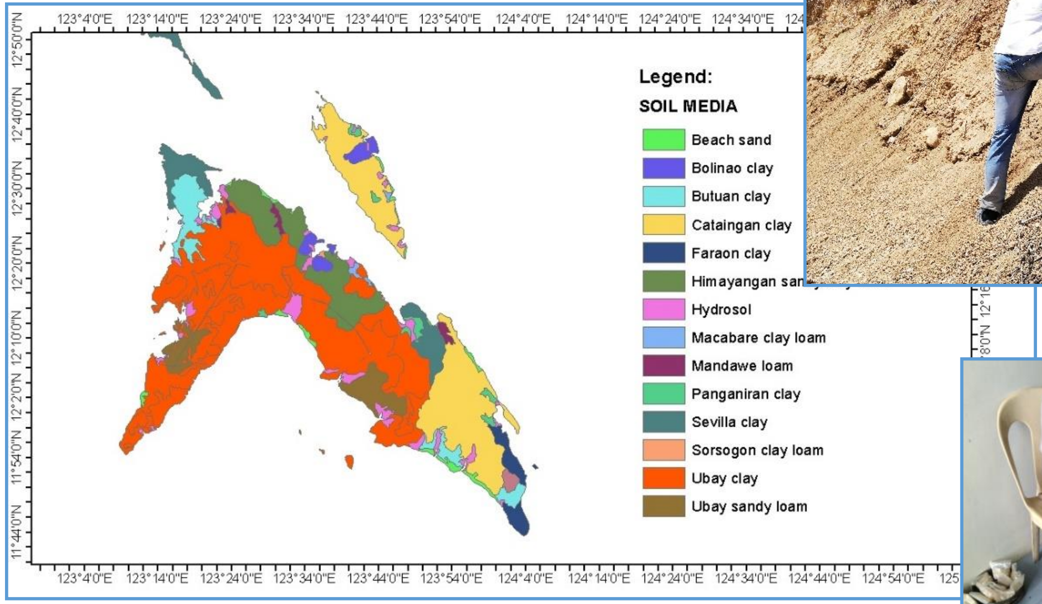
Aquifer Vulnerability Index Map

DATA ACQUSITION AND PROCESSING

Soil **(S)**

Drastic Parameters	Range	Rating	Weight
Soil Media (S)	Thin or Absent	10	
	Gravel	10	
	Sand	9	
	Peat	8	
	Shrinking or Aggregated Clay	7	3
	Sandy Loam	6	
	Loam	5	
	Silty Loam	4	
	Clay Loam	3	
	Manure	2	
	Non-Shrinking Clay	2	

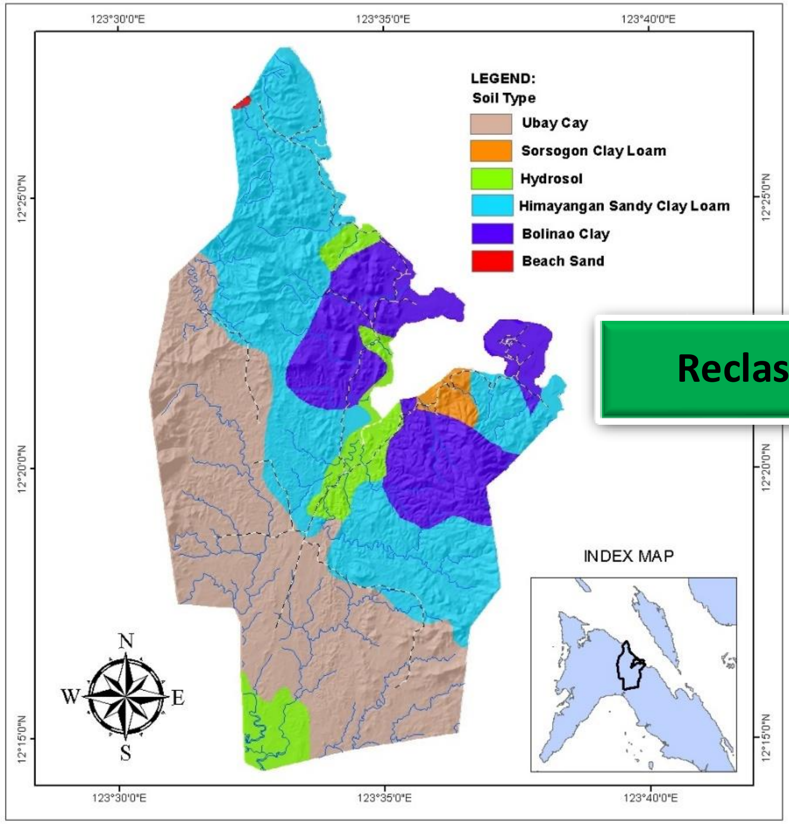
- Represents the uppermost weathered portion of the unsaturated zone and control the amount of recharge that can infiltrate downward



Soil map from BSWM

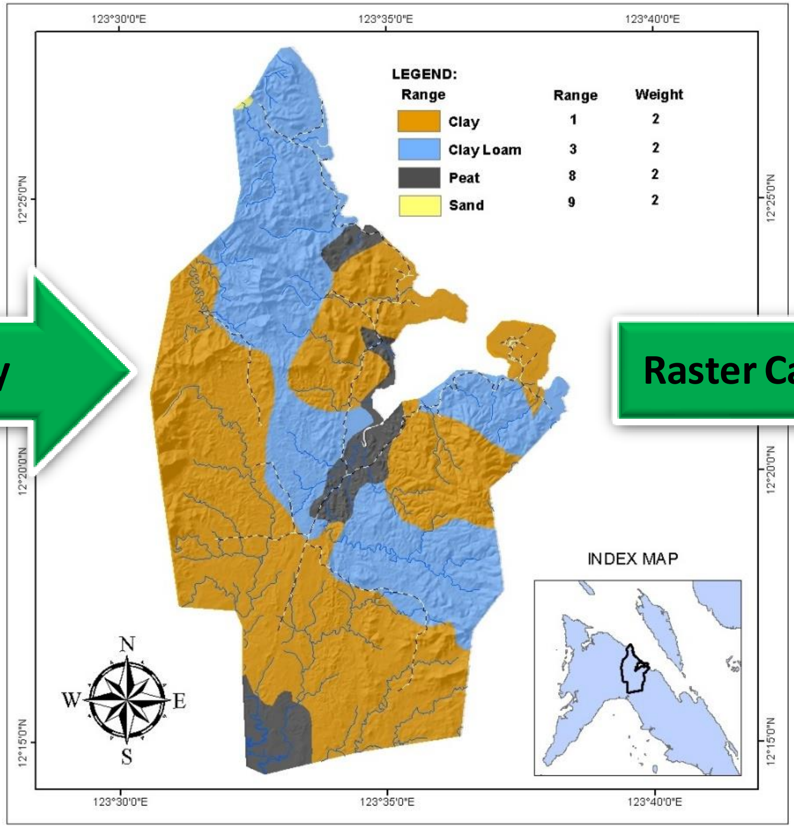
DATA ACQUSITION AND PROCESSING

Soil **(S)**



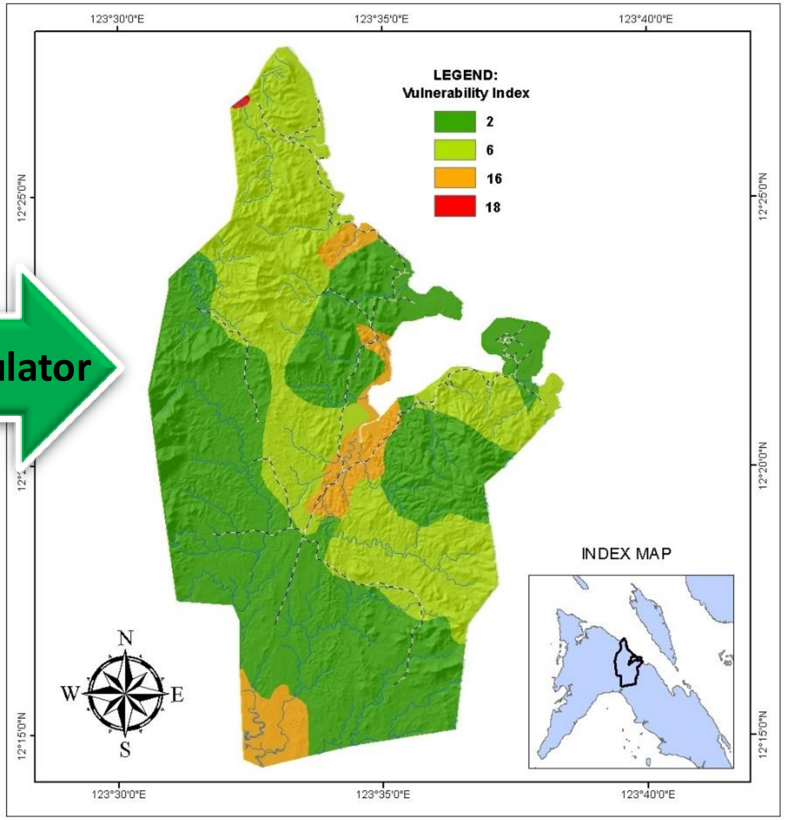
Soil Map

Reclassify



Soil Media Map

Raster Calculator



Soil Media Vulnerability Index Map

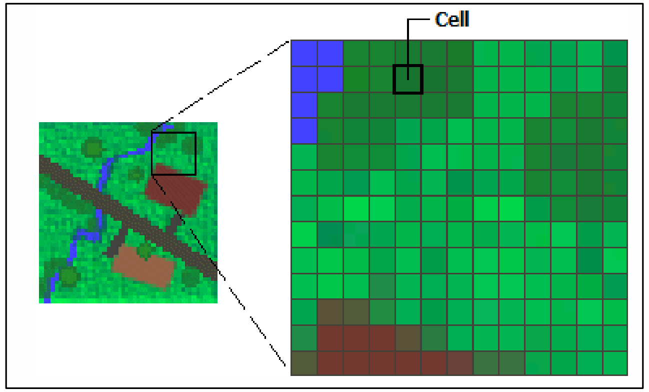
DATA ACQUSITION AND PROCESSING

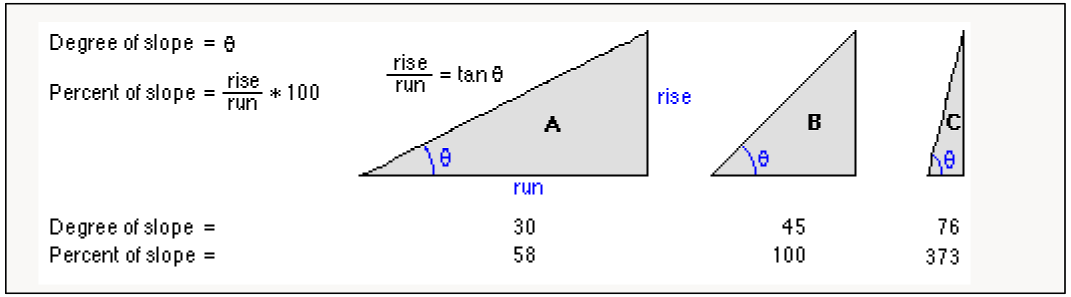
Topography (T)

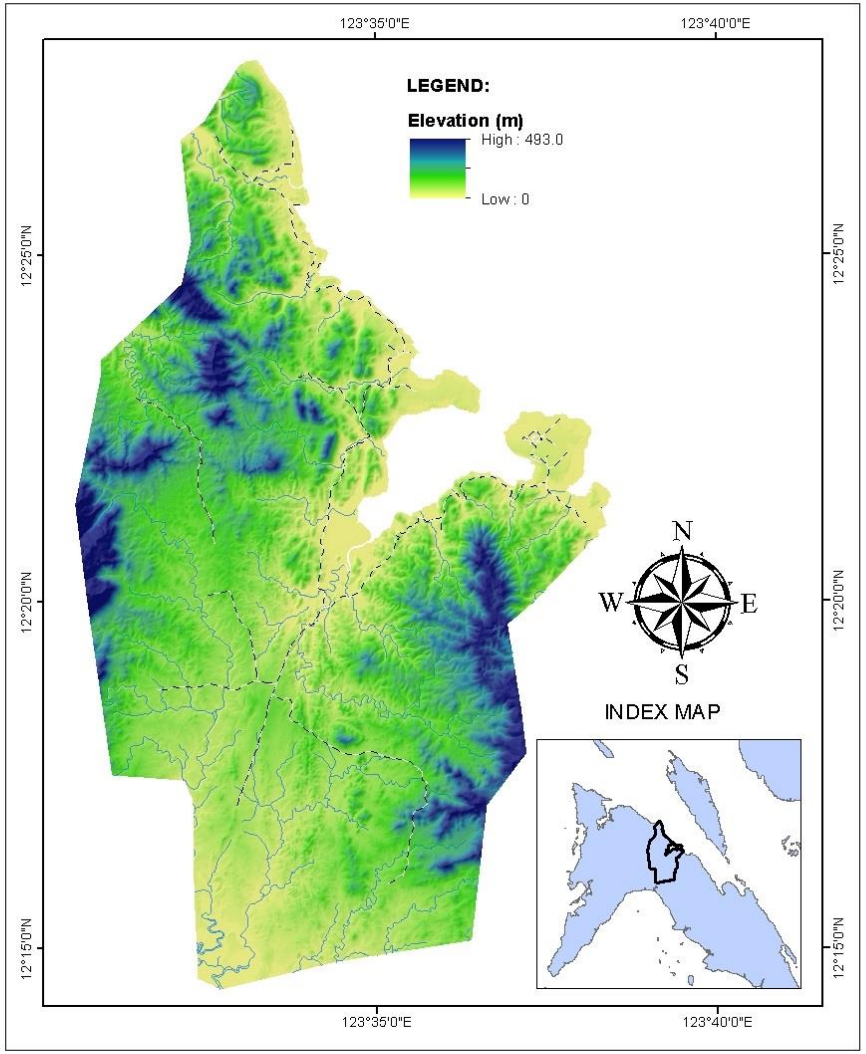
Drastic Parameters	Range	Rating	Weight
Topography (T)	0 – 2% 2 – 6% 6 – 12% 12 – 18% > 18%	10 9 5 3 1	1

- Refers to the slope of the land surface (indicates whether a pollutant will runoff or remain long enough to infiltrate)

5 m Resolution DEM





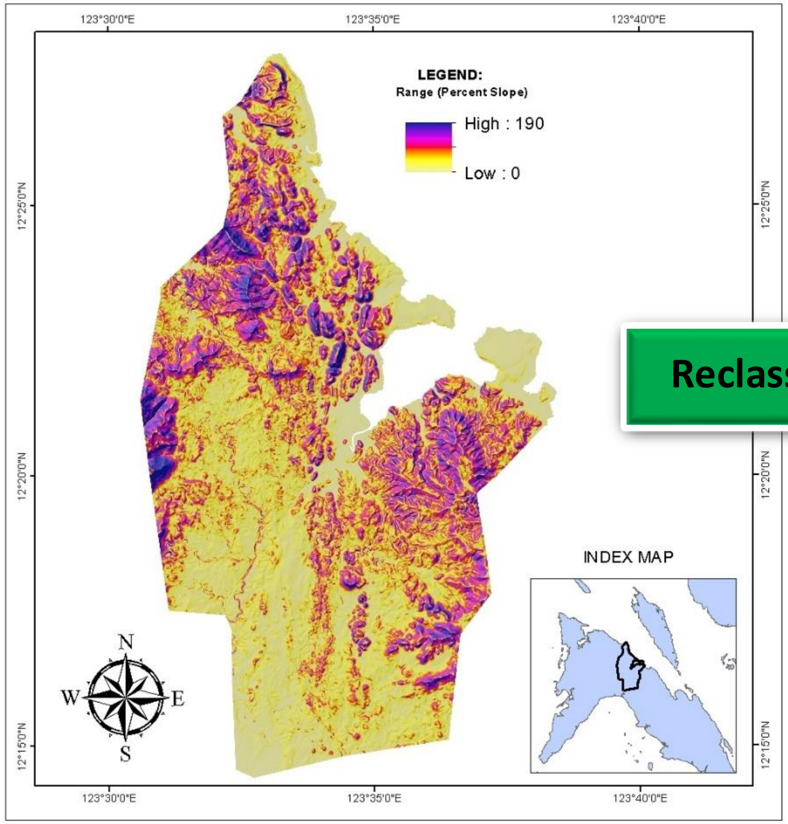


IFSAR* generated Digital Elevation Model (DEM)

*Interferometric Synthetic Aperture Radar

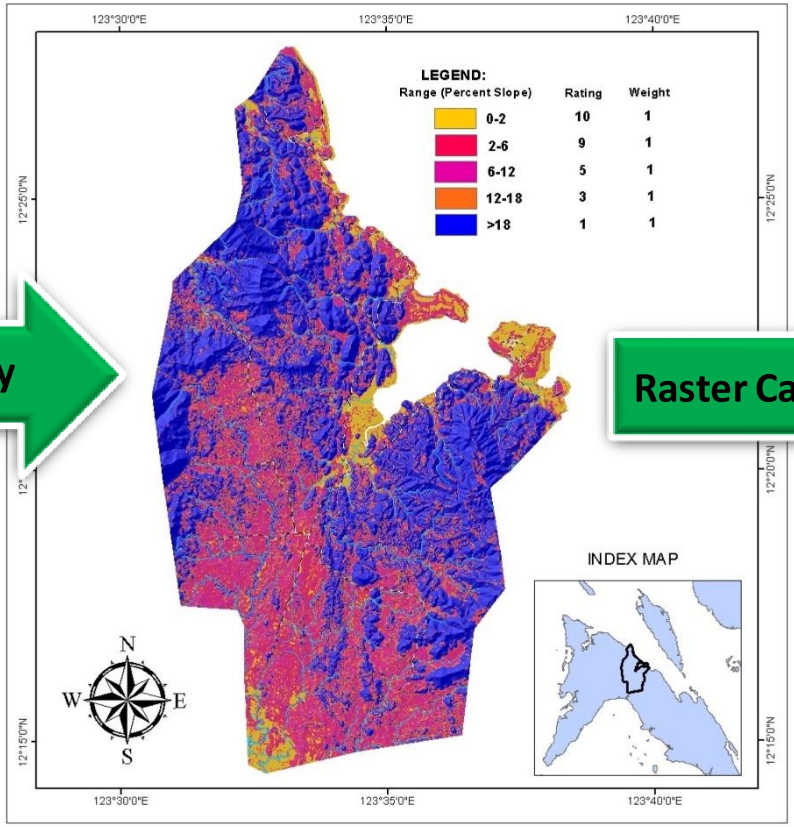
DATA ACQUSITION AND PROCESSING

Topography **(T)**



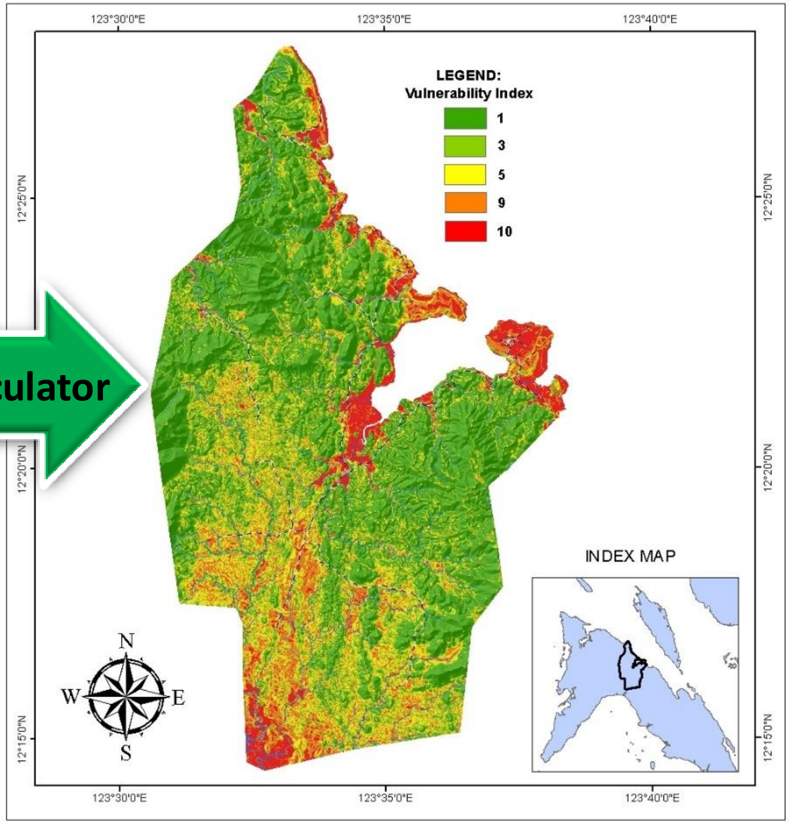
Slope Map

Reclassify



Reclassified Topography (Slope) Map

Raster Calculator



Topography Vulnerability Index Map

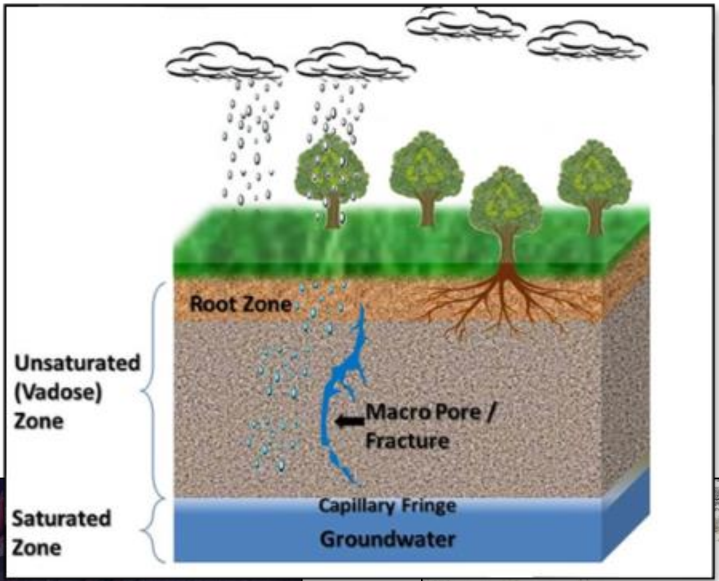
Drastic Parameters	Range	Rating	Weight
Topography (T)	0 – 2%	10	
	2 – 6%	9	**1**
	6 – 12%	5	
	12 – 18%	3	
	> 18%	1	

DATA ACQUSITION AND PROCESSING

Impact of Vadose Zone **(I)**

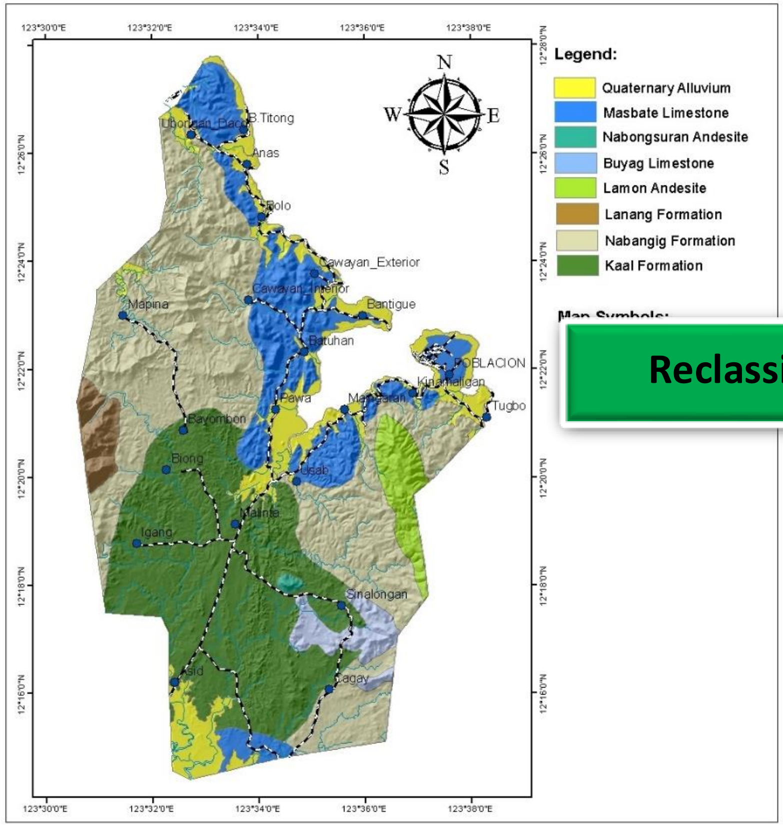
Drastic Parameters	Range	Rating	Weight
Impact of Vadose Zone (I)	Silt/Clay	3	**5**
	Shale	3	
	Limestone	5	
	Sandstone	5	
	Bedded Limestone, Sandstone	6	
	Sand and Gravel with significant silt and clay	6	
	Metamorphic/Igneous	4	
	Sand and Gravel	8	
	Basalt	9	
	Karst Limestone	10	

- Controls the passage and attenuation of the contaminated material to the saturated zone



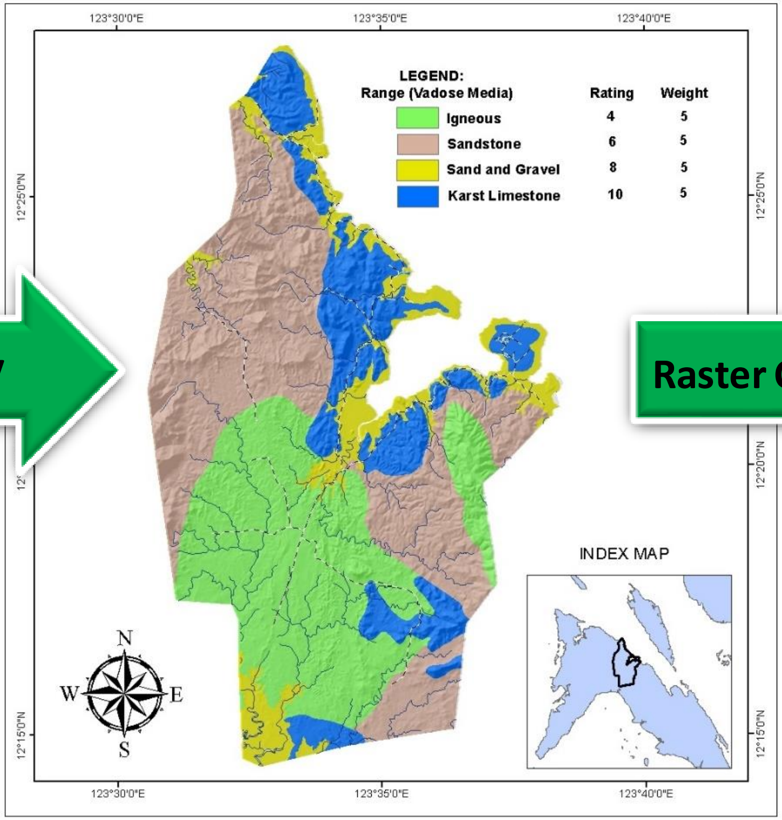
DATA ACQUSITION AND PROCESSING

Impact of Vadose Zone (I)



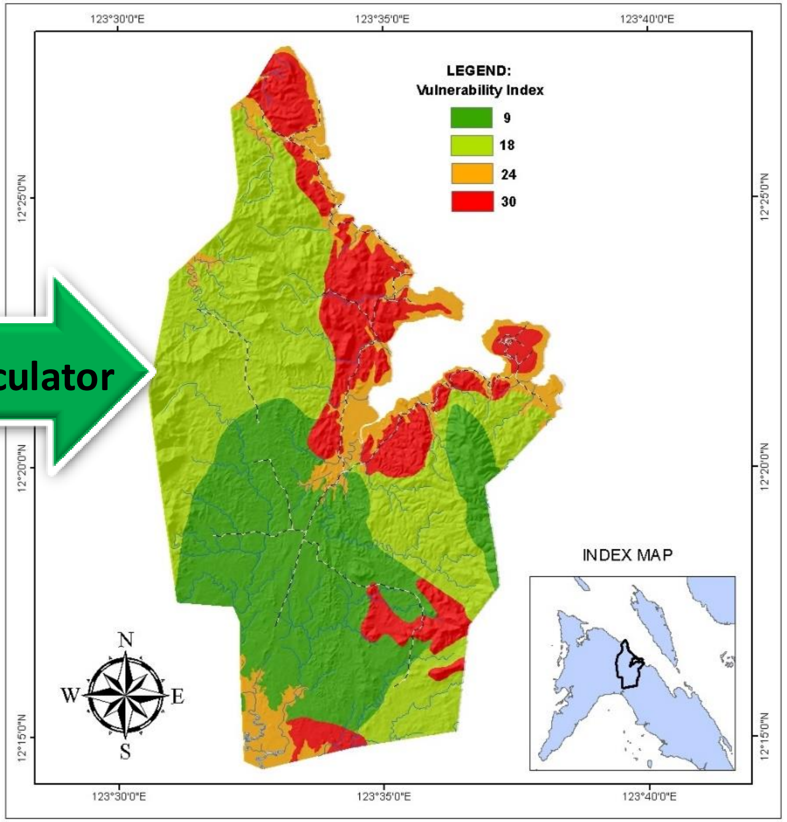
Geologic Map

Reclassify



Impact of Vadose Zone Map Map

Raster Calculator



Impact of Vadose Zone Vulnerability Index Map

DATA ACQUSITION AND PROCESSING

Hydraulic Conductivity **(C)**

Drastic Parameters	Range	Rating	Weight
Hydraulic Conductivity **(K)**	0.04 – 4.08 m/day 4.09 – 12.25 m/day 12.26 – 28.6 m/day 28.7 – 40.80 m/day 40.81 – 81.62 m/day > 81.62 m/day	1 2 4 6 8 10	**3**

- ➢ Indicates the ability of the aquifer to transmit water, hence determines the rate of flow of contaminant material within the groundwater system

Table 3.2 **Representative Values of Hydraulic Conductivity for Various Rock Types**

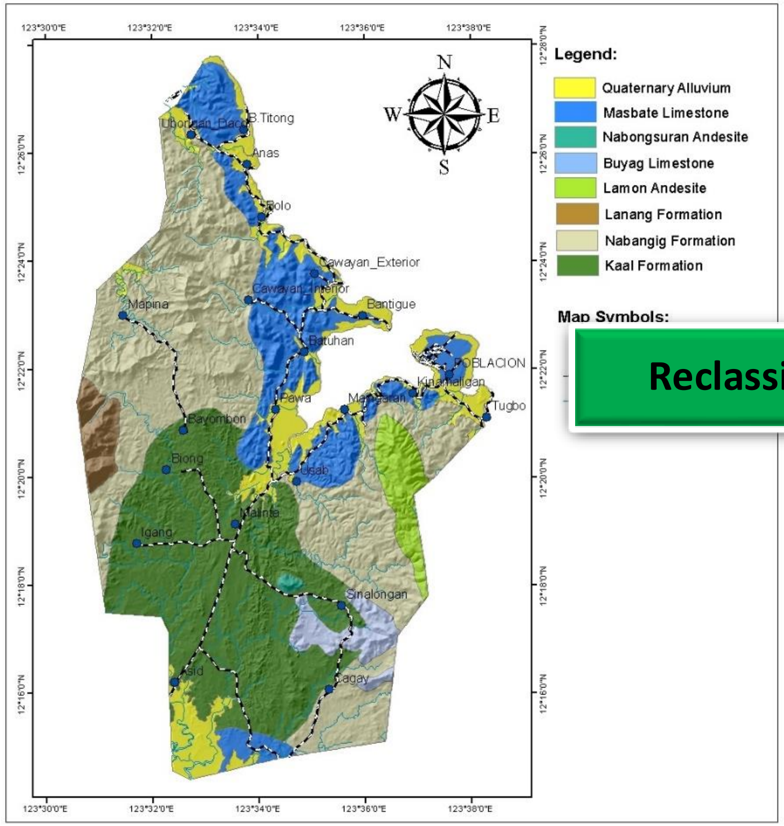
Material	Hydraulic Conductivity (m/s)
SEDIMENTARY	
Gravel	3×10^{-4}–3×10^{-2}
Coarse sand	9×10^{-7}–6×10^{-3}
Medium sand	9×10^{-7}–5×10^{-4}
Fine sand	2×10^{-7}–2×10^{-4}
Silt, loess	1×10^{-9}–2×10^{-5}
Till	1×10^{-12}–2×10^{-6}
Clay	1×10^{-11}–4.7×10^{-9}
Unweathered marine clay	8×10^{-13}–2×10^{-9}
SEDIMENTARY ROCKS	
Karst and reef limestone	1×10^{-6}–2×10^{-2}
Limestone, dolomite	1×10^{-9}–6×10^{-6}
Sandstone	3×10^{-10}–6×10^{-6}
Siltstone	1×10^{-11}–1.4×10^{-8}
Salt	1×10^{-12}–1×10^{-10}
Anhydrite	4×10^{-13}–2×10^{-8}
Shale	1×10^{-13}–2×10^{-9}
CRYSTALLINE ROCKS	
Permeable basalt	4×10^{-7}–2×10^{-2}
Fractured igneous and metamorphic rock	8×10^{-9}–3×10^{-4}
Weathered granite	3.3×10^{-6}–5.2×10^{-5}
Weathered gabbro	5.5×10^{-7}–3.8×10^{-6}
Basalt	2×10^{-11}–4.2×10^{-7}
Unfractured igneous and metamorphic rocks	3×10^{-14}–2×10^{-10}

Physical and Chemical Hydrogeology
Second Edition (1990)
Patrick A. Domenico Franklin W. Schwartz

DATA ACQUSITION AND PROCESSING

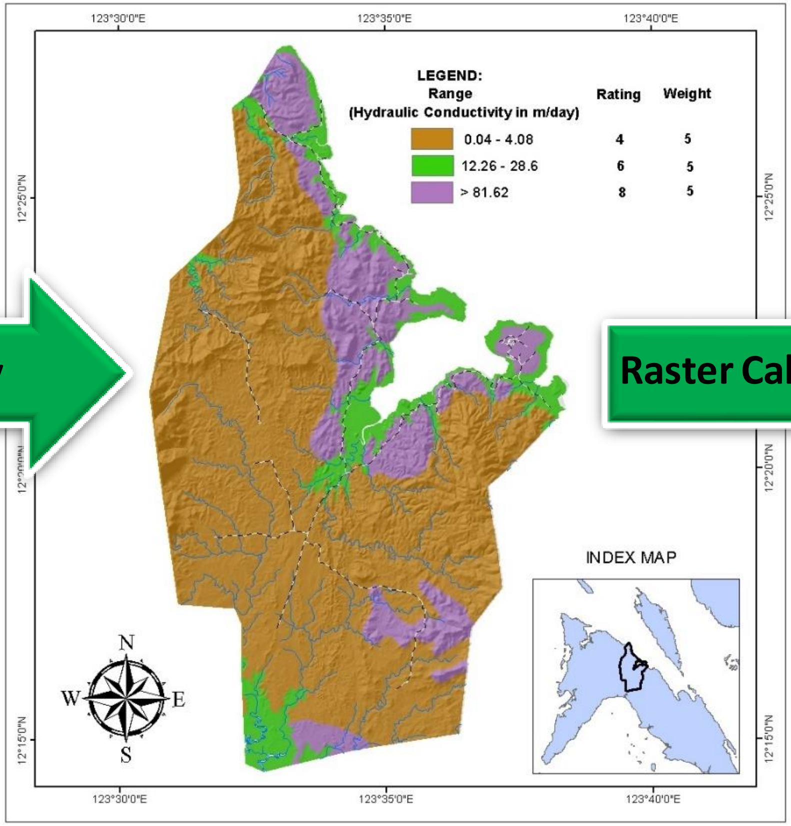
Hydraulic Conductivity **(C)**

Drastic Parameters	Range	Rating	Weight
Hydraulic Conductivity **(K)**	0.04 – 4.08 m/day	1	
	4.09 – 12.25 m/day	2	
	12.26 – 28.6 m/day	4	**3**
	28.7 – 40.80 m/day	6	
	40.81 – 81.62 m/day	8	
	> 81.62 m/day	10	



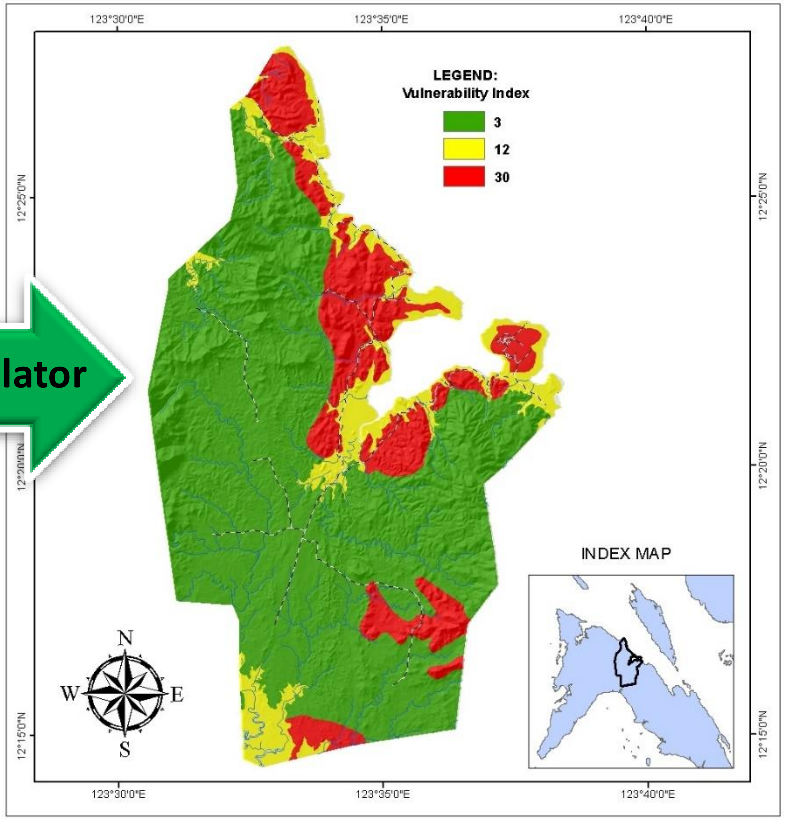
Geologic Map

Reclassify



Hydraulic Conductivity Map

Raster Calculator



Hydraulic Conductivity Vulnerability Index Map

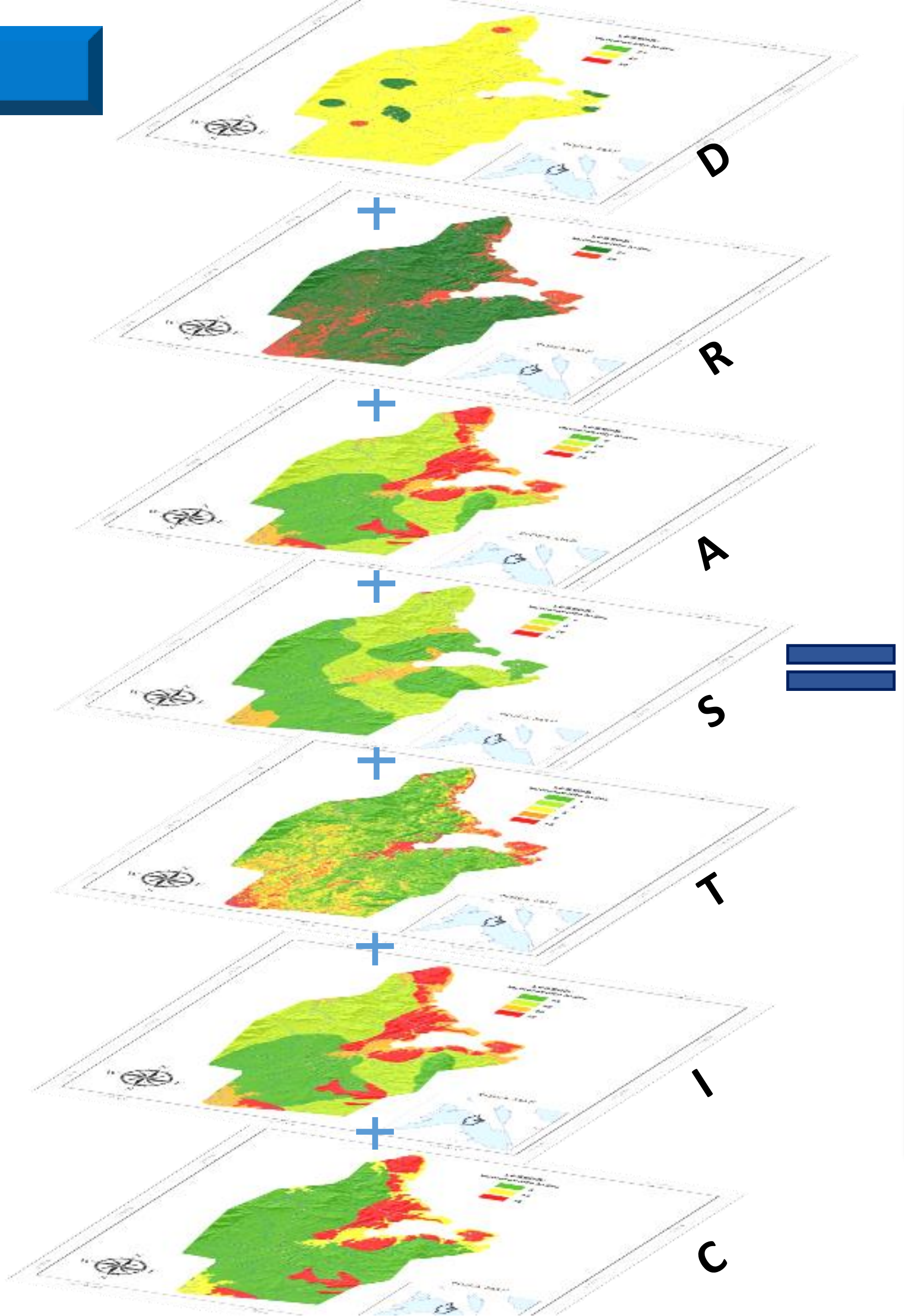
DATA ACQUSITION AND PROCESSING

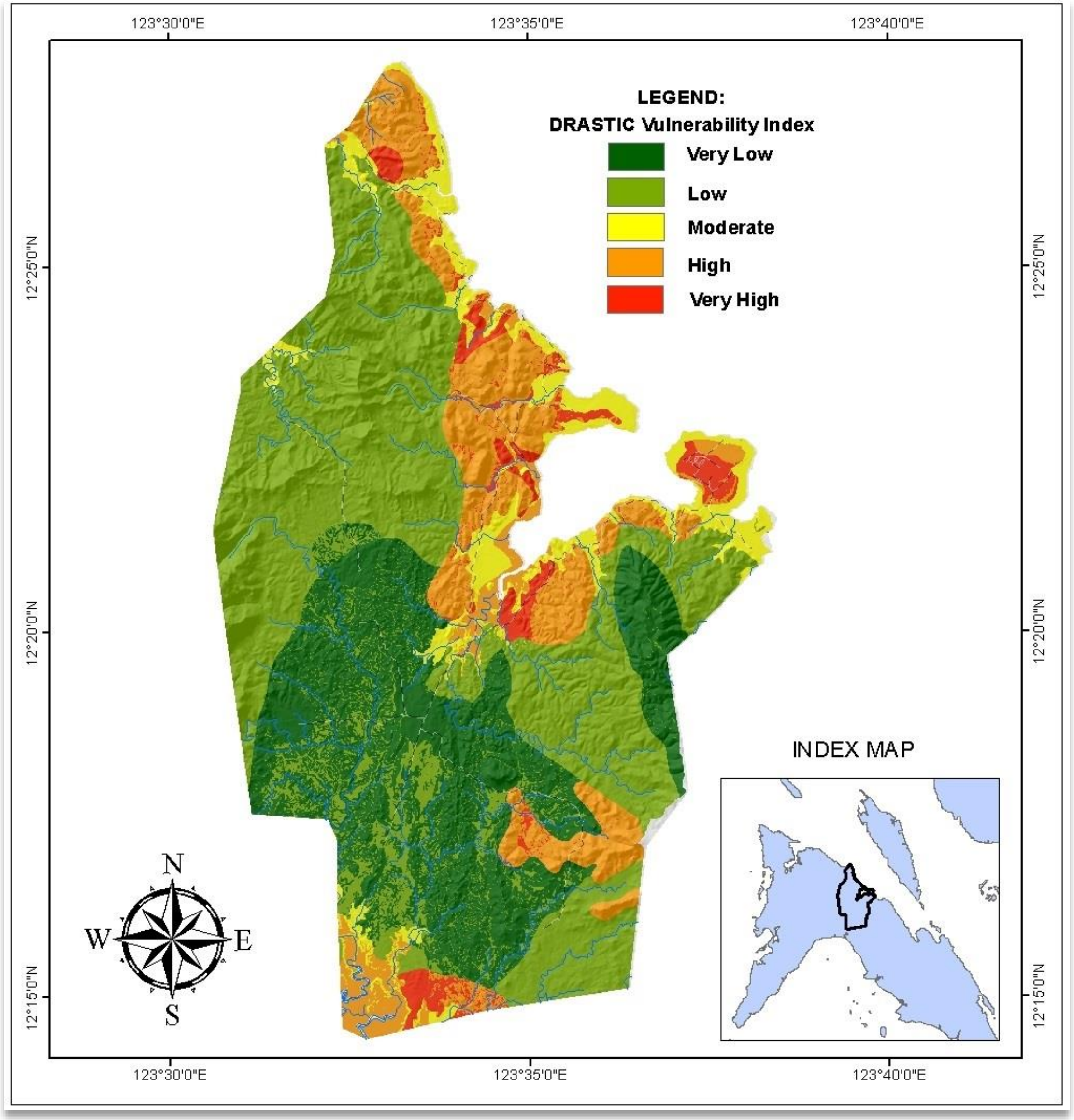
The DRASTIC Vulnerability Index (DVI) is calculated by linear addition of the weights and rating as follows:

$$DVI = D_rD_w + R_rR_w + A_rA_w + S_rS_w + T_rT_w + I_rI_w + C_rC_w$$

Where:
D_r = Rating for the depth to water table;
D_w = Weight assigned to the depth to water table;
R_r = Rating for aquifer recharge;
R_w = Weight for aquifer recharge;
A_r = Rating assigned to aquifer media
A_w = Weight assigned to aquifer media
S_r = Rating for the soil media
S_w = Weight for the soil media
T_r = Rating for topography/slope
T_w = weight assigned to topography/slope
I_r = Rating assigned to impact of vadose zone
I_w = Weight assigned to impact of vadose zone
C_r = Rating for rates of hydraulic conductivity
C_w = Weight given to hydraulic conductivity

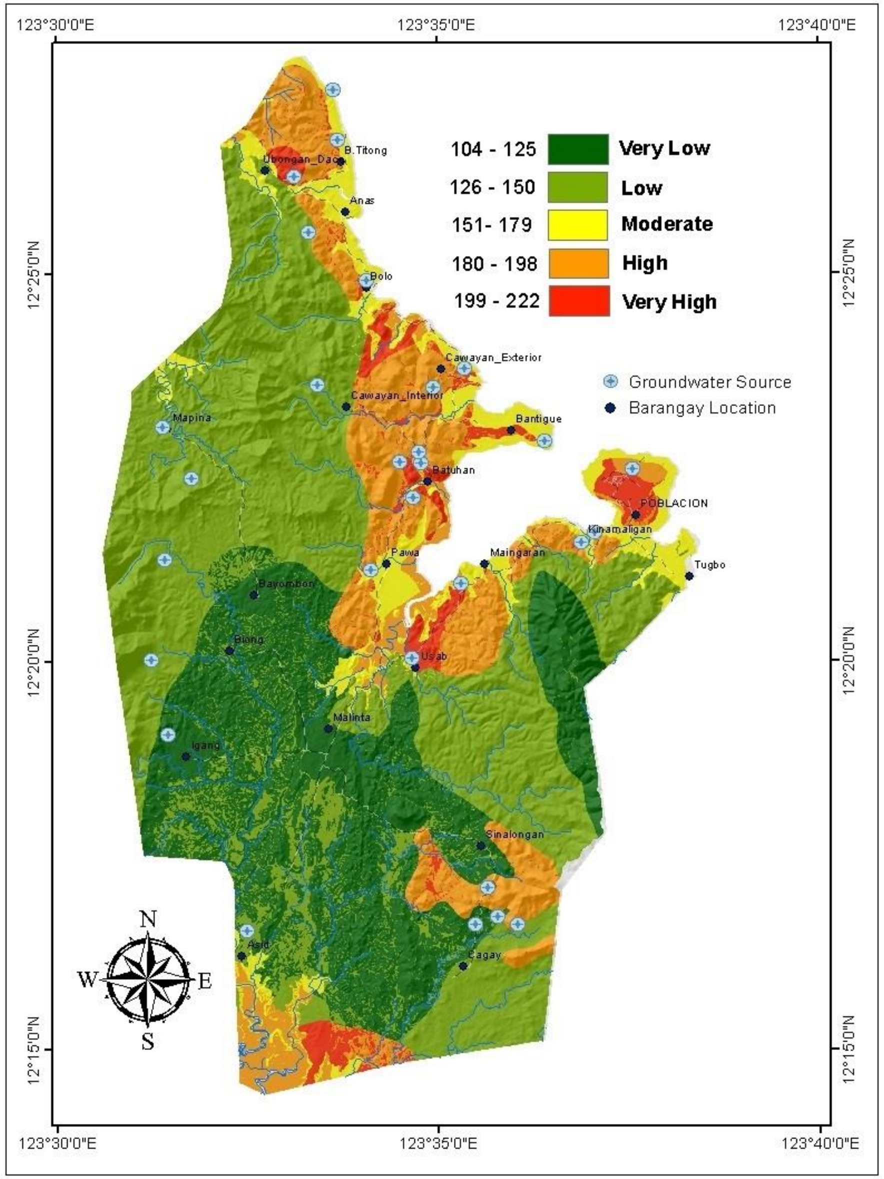
RESULTS





DRASTIC VULNERABILITY INDEX MAP

RESULTS (DRASTIC Method)



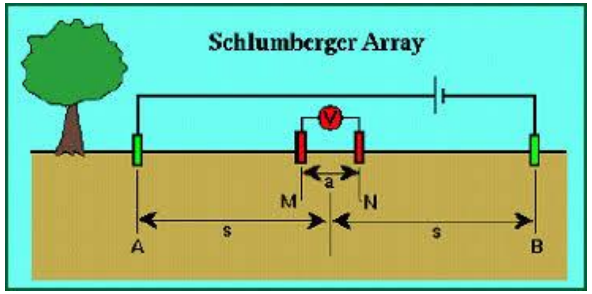
DRASTIC VULNERABILITY INDEX MAP

Classification	Area in km²	Area in %
Very Low	48.57	25.75%
Low	86.20	45.70%
Moderate	15.12	8%
High	30.91	16.40%
Very High	7.79	4.13%

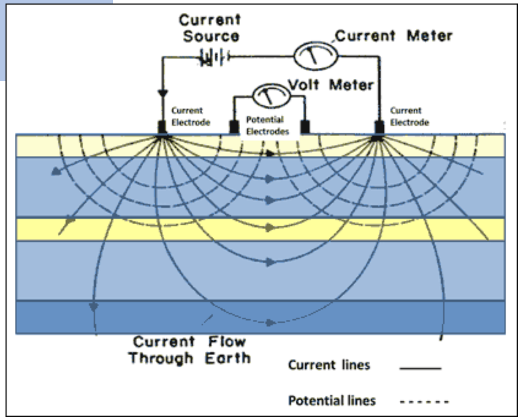
Natural Break (Jenks) – one of the data clustering methods designed to determine the best arrangement of values into different classes

METHODOLOGY (Seawater Intrusion Mapping)

- Vertical Electrical Sounding (VES) points (*Schlumberger array*) were carried out in the coastal areas in Masbate City using the geo-resistivity meter SYSCAL R1 Plus model

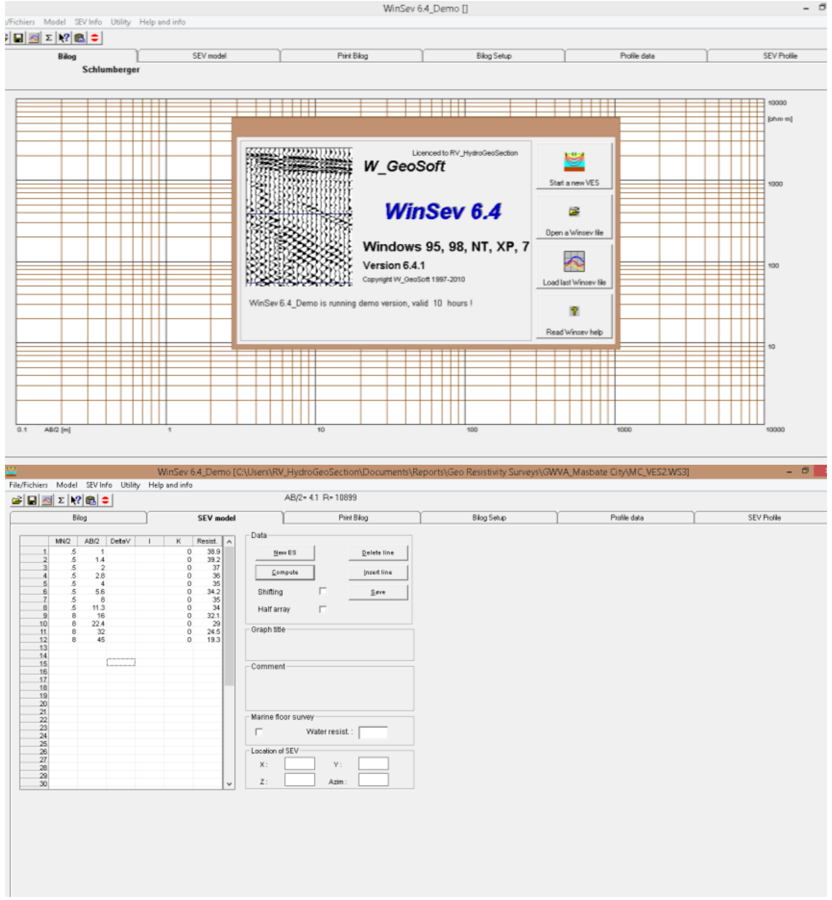


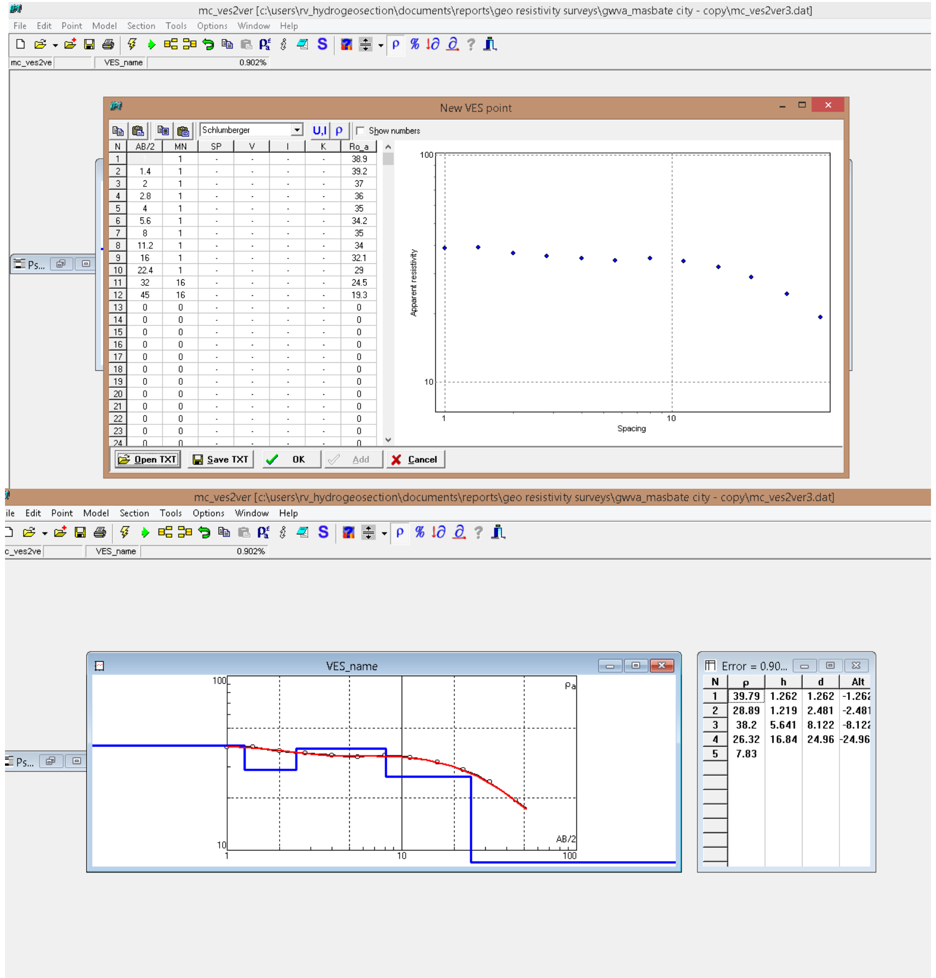
- Electrical resistivity measurements are made by passing electrical current through the ground using a pair of electrodes (current electrodes) while measuring the resultant voltage field in the ground at another pair of electrodes (potential electrodes)



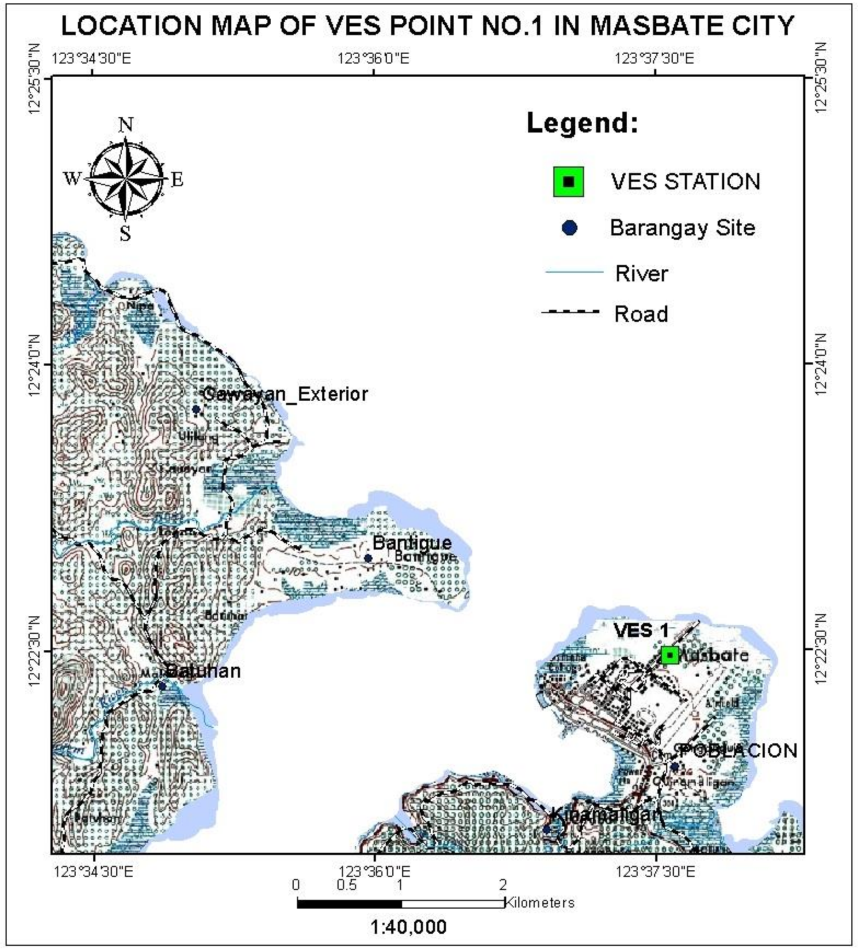
METHODOLOGY (Seawater Intrusion Mapping)

- IPI2Win and Winsev ver. 6 software were used to interpret different resistivity layers and come out with a layered resistivity model





RESULTS (Seawater Intrusion Mapping)

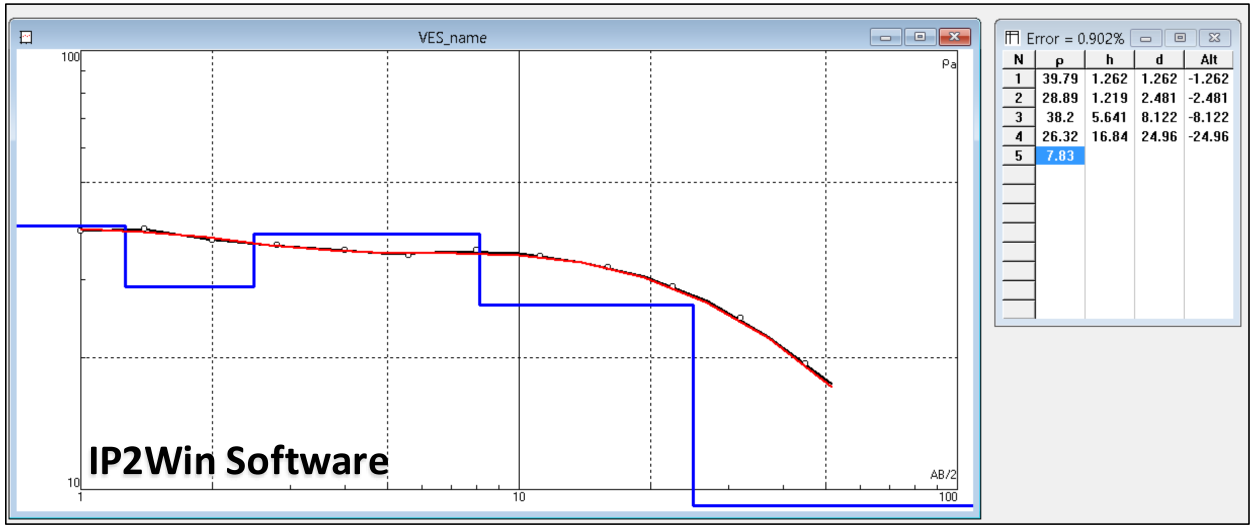


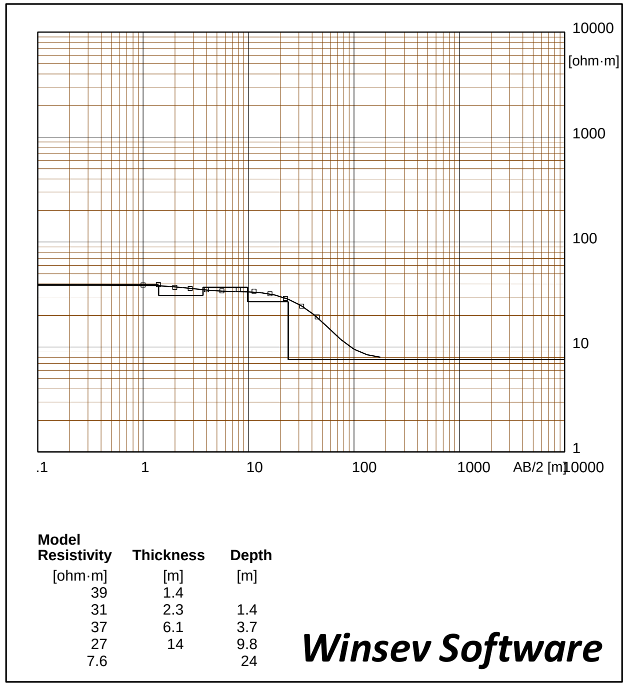
Location: Barangay Ibiñgay, Masbate City

Geographic Coordinates: 12˚ 22' 28.4'' N and 123˚ 37' 34.6'' E

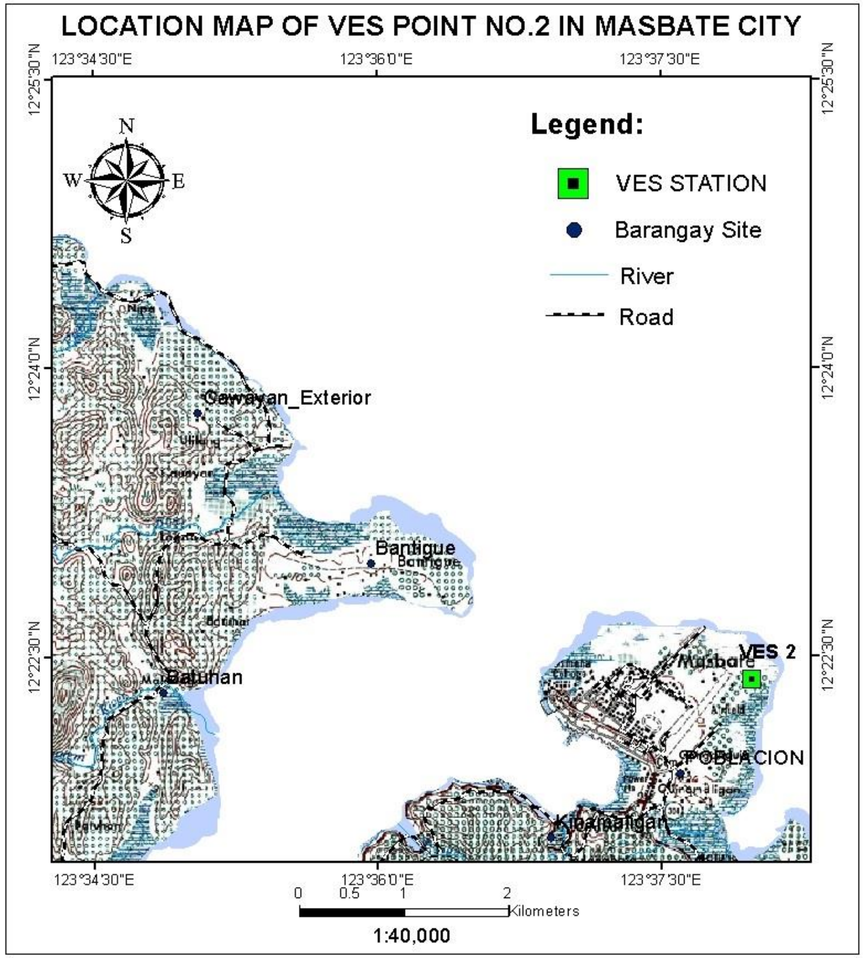
Elevation: 5 m.a.s.l

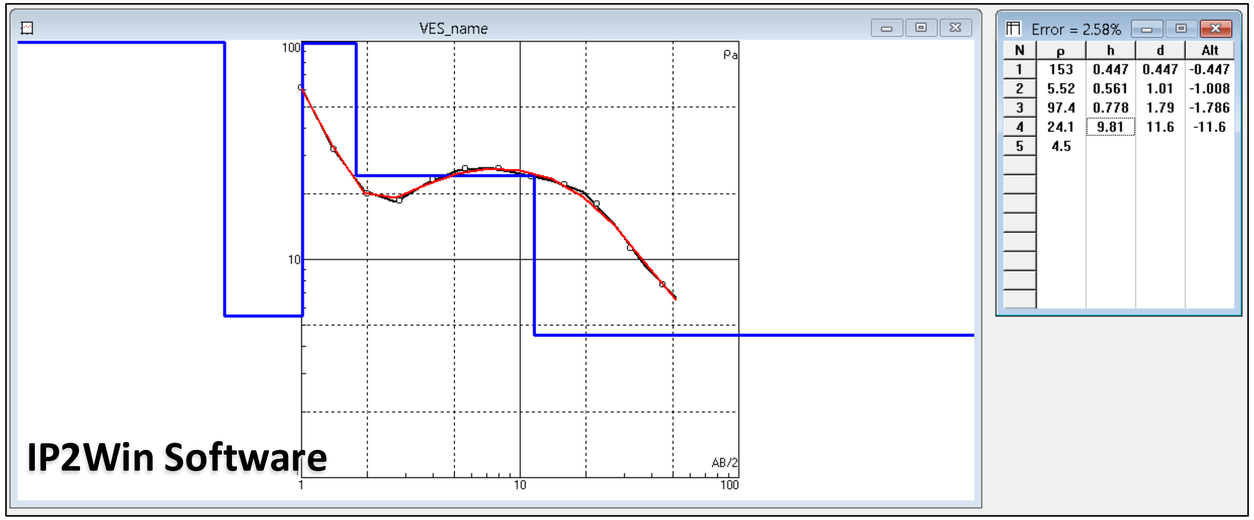
Depth of Freshwater-Seawater Interface: ≈ 25 m.b.g.s.

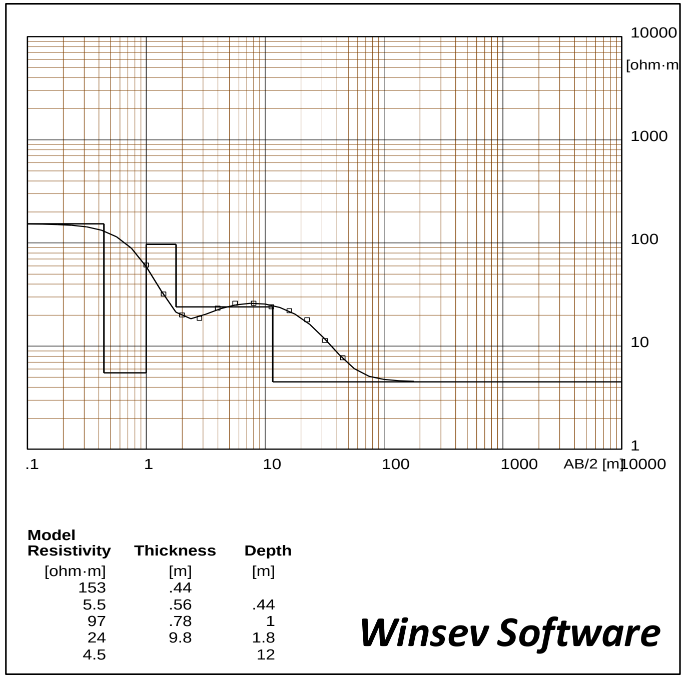




RESULTS (Seawater Intrusion Mapping)







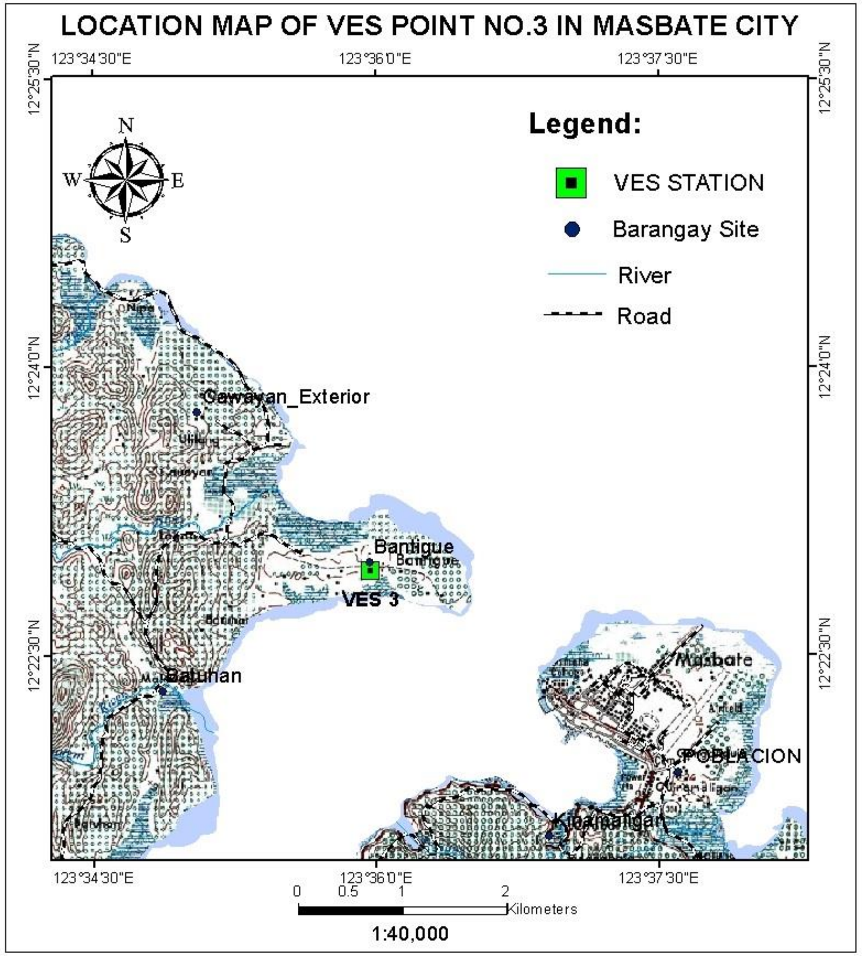
Location: Barangay Nursery, Masbate City

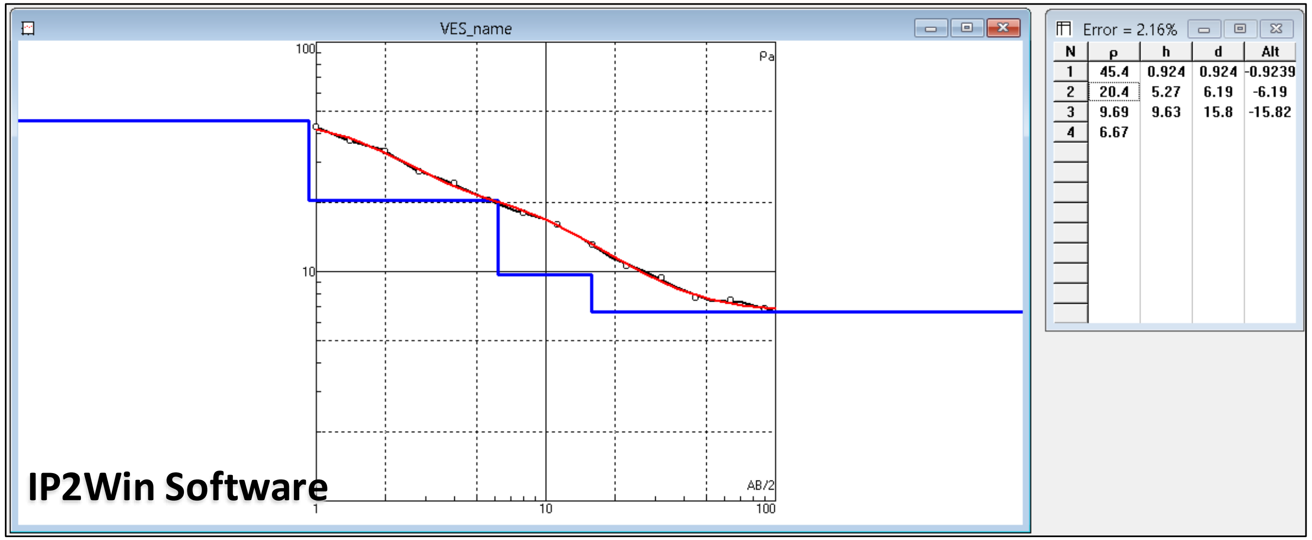
Geographic Coordinates: 12˚ 22’ 22.9’’ N and 123˚ 37’ 58.6’’ E

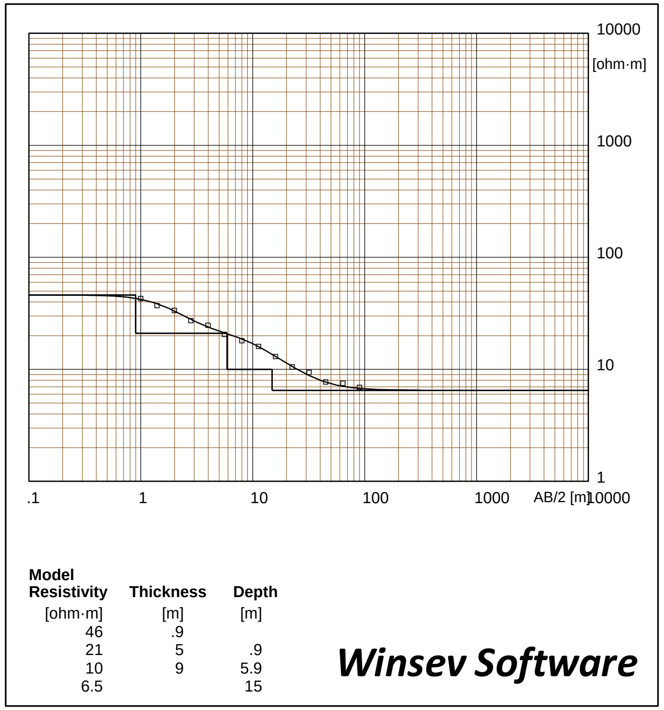
Elevation: 6 m.a.s.l

Depth of Freshwater-Seawater Interface: ≈ 12 m.b.g.s.

RESULTS (Seawater Intrusion Mapping)







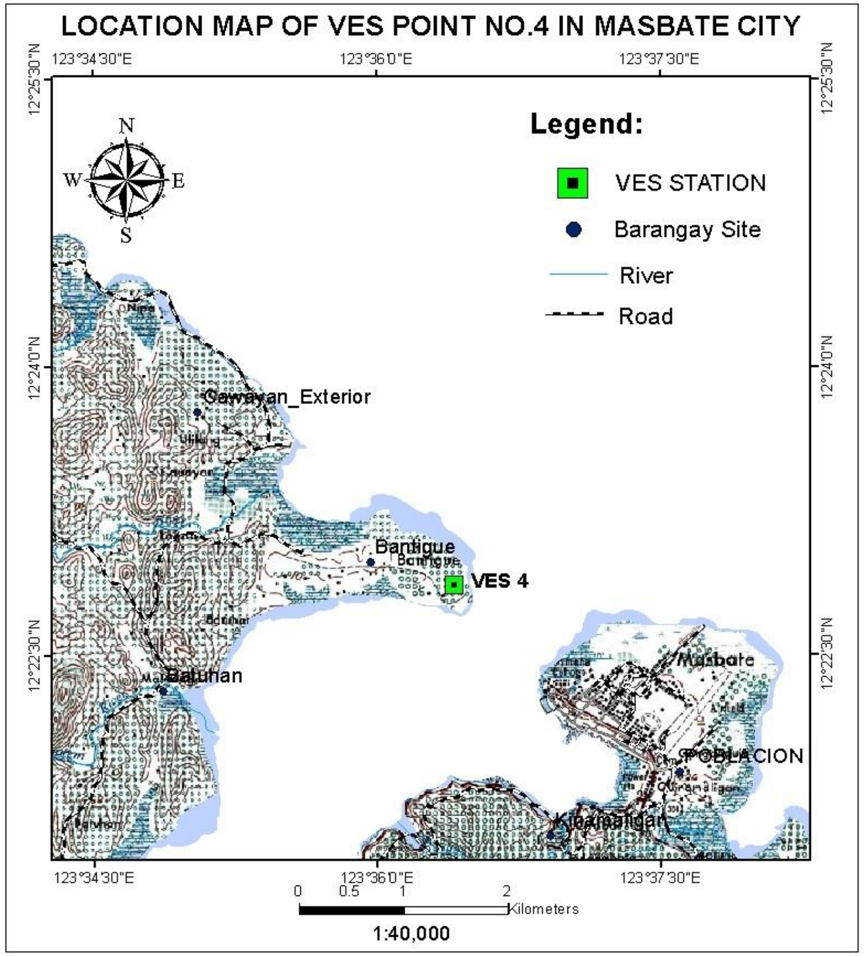
Location: Barangay Nursery, Masbate City

Geographic Coordinates: 12˚ 22’ 26.5’’ N and 123˚ 35’ 58.2’’ E

Elevation: 10 m.a.s.l.

Depth of Freshwater-Seawater Interface: ≈ 15 m.b.g.s.

RESULTS (Seawater Intrusion Mapping)

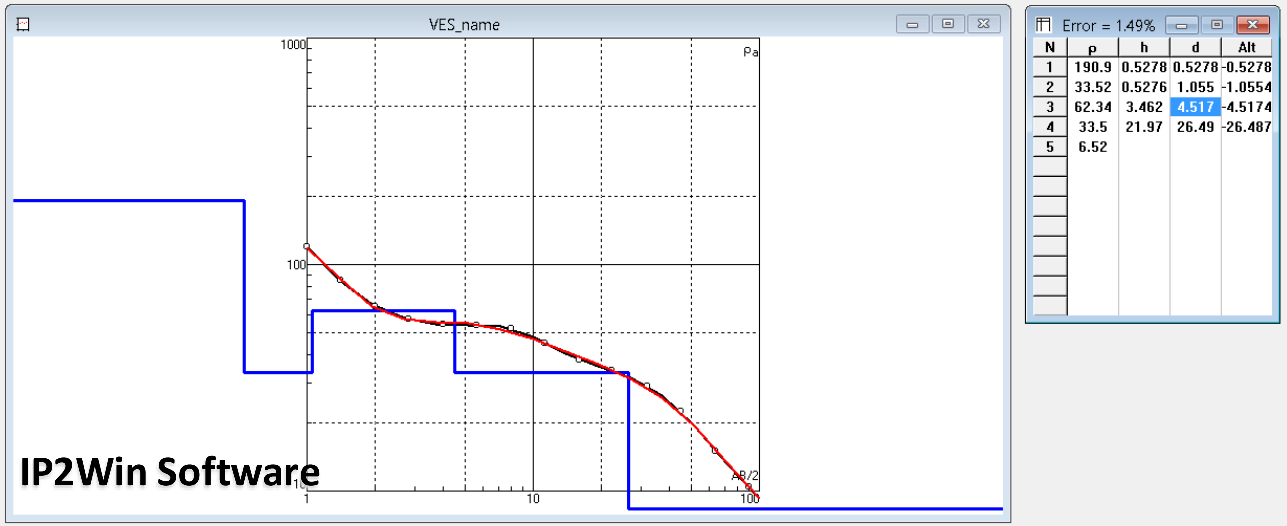


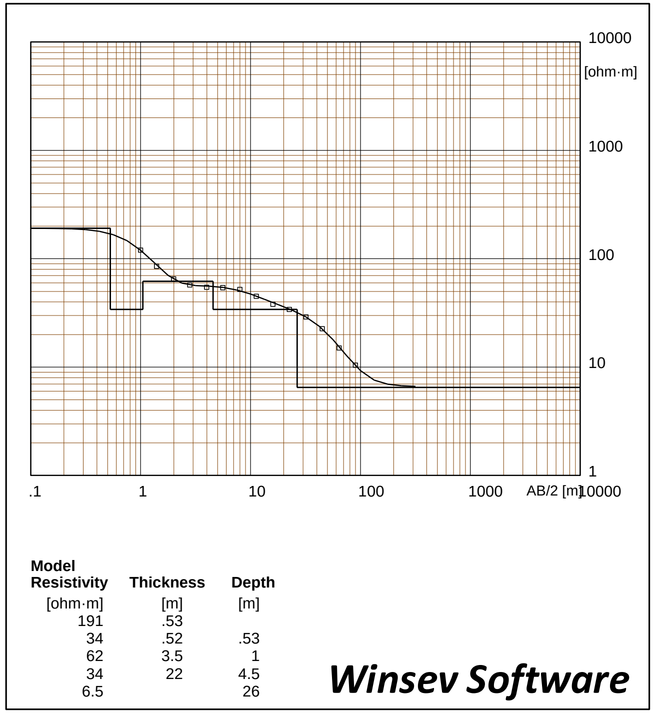
Location: Barangay Bantigue, Masbate City

Geographic Coordinates: 12˚ 22’ 52.1’’ N and 123˚ 36’ 24.6’’ E

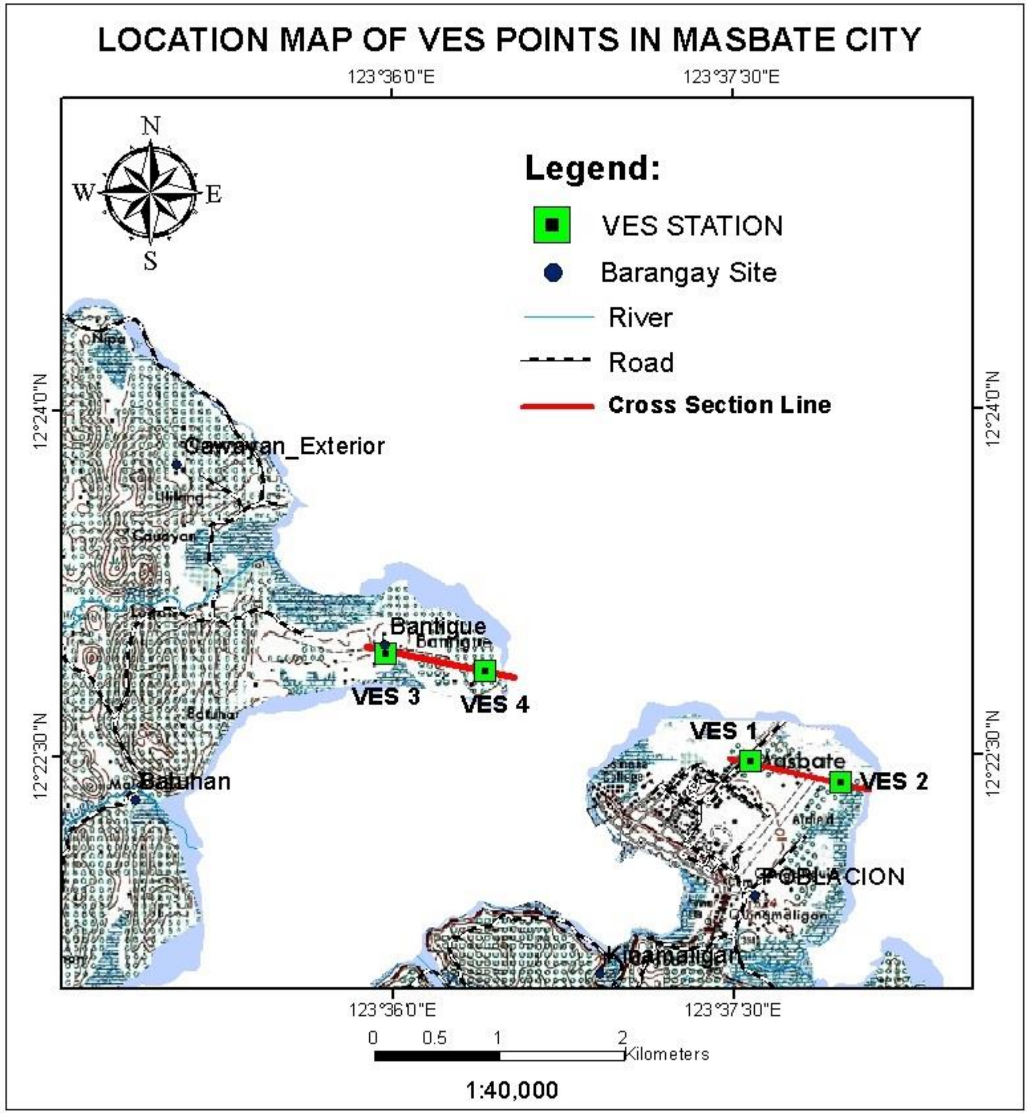
Elevation: 6 m.a.s.l.

Depth of Freshwater-Seawater Interface: ≈ 25 m.b.g.s.



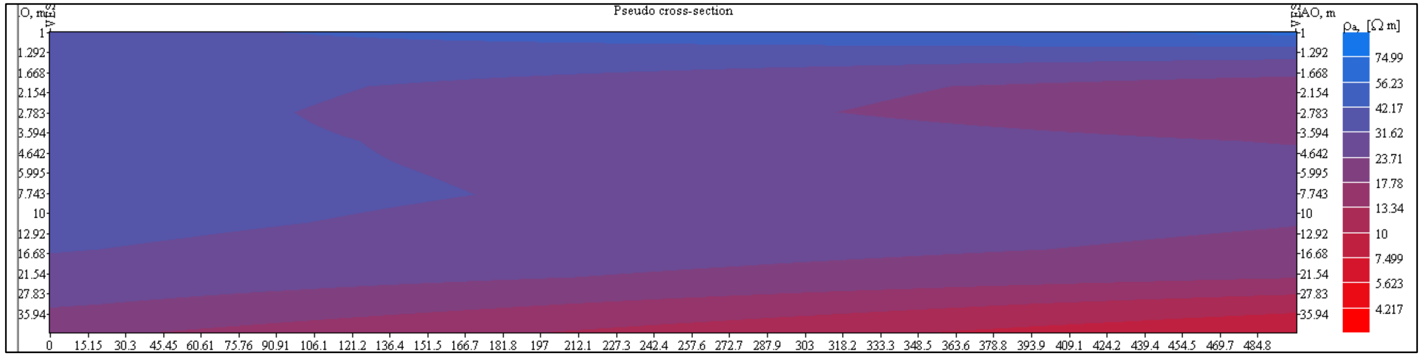


RESULTS (Seawater Intrusion Mapping)



VES 1

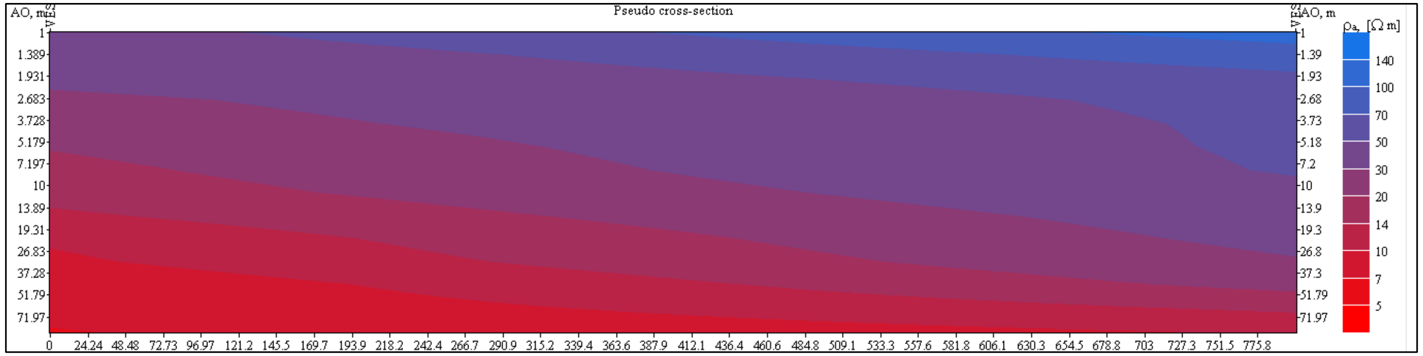
VES 2



Cross Section Profile of VES 1 to VES 2

VES 3

VES 4



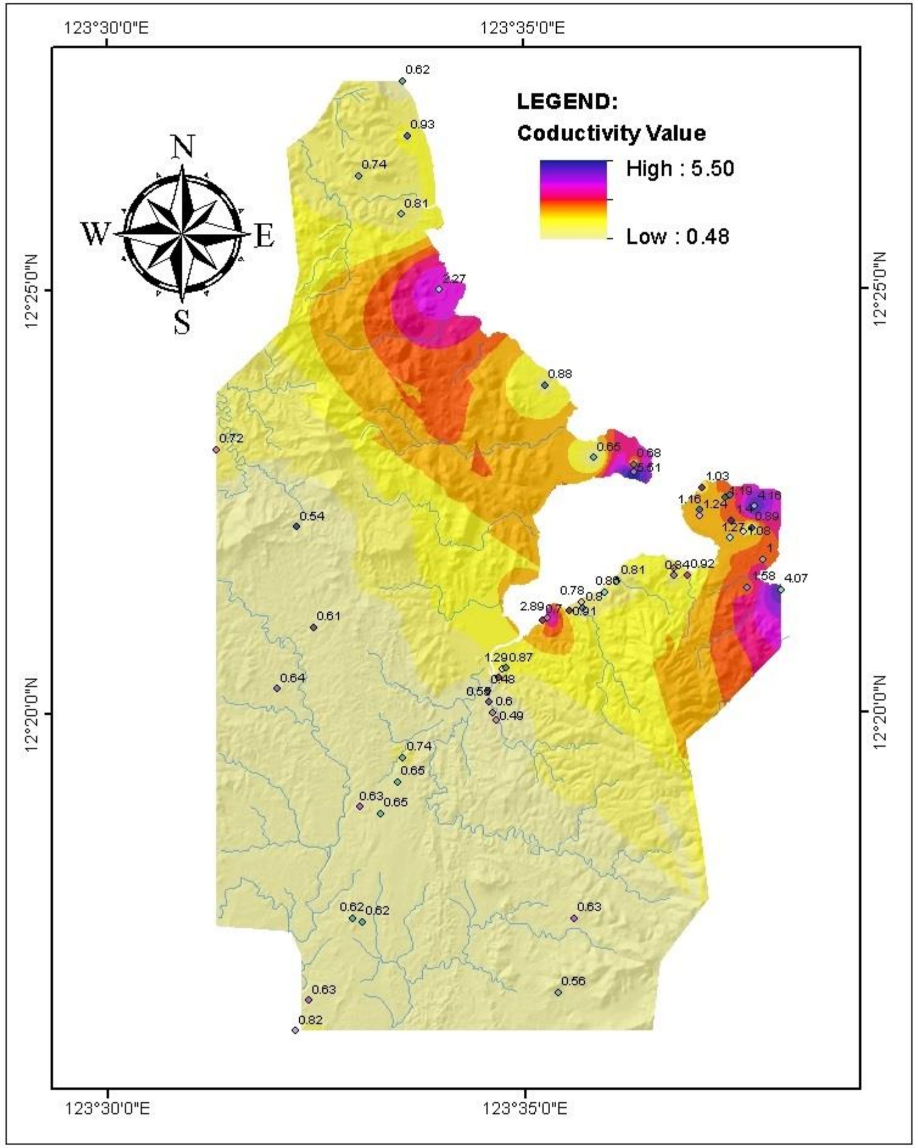
Cross Section Profile of VES 1 to VES 2

RESULTS (Seawater Intrusion Mapping)

Min: 0.48 S/m

Max: 5.50 S/m

Mean: 1.12 S/m



Electrical Conductivity Map of Masbate City

CONCLUSIONS

- This study was performed using a GIS model and the DRASTIC index method to determine the vulnerability of ground-water in Masbate City
- The DRASTIC Vulnerability Index was computed between 104 - 222. Using Natural Break (Jenks), these values were reclassified into five classes (VL, L, M, H, VH).
- The resulting DRASTIC Vulnerability map shows that the areas with **Very High** vulnerability rating (7.79 km^2) is largely underlain by Masbate Limestone aquifer with (7.11 km^2 or 99.95%)
- Areas with **High** vulnerability rating (30.91 km^2) are mostly underlain by Masbate Limestone (20.82 km^2 or 66.77%), Buyag Limestone (4.90 km^2 or 15.71%) and Alluvium (5.46 $km^2$17.51%)
- **Moderate** vulnerability rating largely corresponds to the Alluvium aquifer (14.9 km^2 or 99%)

CONCLUSIONS

- The vulnerability map obtained from the DRASTIC method gives location which must have high priority in terms of aquifer protection and pollution prevention that could be utilized by LGU Masbate City for their groundwater management plan.
- interpretation of the VES data concludes that 2 out of 4 sounding curves (VES 1 and VES 4)are KQ-type indicating freshwater horizon in the upper layer while the other 2 sounding curves (VES 2 and VES 3) are of Q-type indicating salinity towards depth
- The depth to the saline-fresh water interface interpreted varied from 12 - 25 m.b.g.s.
- Results of geo-resistivity survey and in-situ water testing of wells show that the process of salt water intrusion is active on coastal barangays of Masbate City.

Thank you for listening!!!