PROJECT SUMMARY REPORT
Mapping High Risk Cholera Zones in Harare, Zimbabwe

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Date: 1st June 2019
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Project Background

Cholera has become a perennial disease in Harare with high morbidity and mortality. This is due to a growing population putting increasing stress on ageing and outdated infrastructure that is no longer able to effectively deal with tap water delivery and waste water management. Drilling a borehole or constructing a shallow well are often used as private solutions to the City's water crisis. However contaminated water that enters the cities underground aquifers is a risk to all well/borehole owners. The goal of the project was to model and map groundwater vulnerability to cholera and other water borne diseases in Harare.

Technical Approach

Cholera Risk was modelled using Geographic Information Systems (GIS) software and the Analytical Hierarchy Process (AHP). Physical natural and anthropogenic factors (or properties) that impact on groundwater vulnerability were identified. These properties were available as spatial data, usually as raster images or shape files. The relative impact of the different properties on groundwater vulnerability was assessed using AHP matrices. This then provided the framework for combining the various input data layers to produce a final composite risk map of groundwater vulnerability to cholera.

The factors/inputs chosen for the project included:

- Sewer Pipe Network
- Population Density
- Depth to Groundwater
- Geological Faults
- Soil Permeability
- Fissure Flow
- Topographic Wetness Index

What does the AHP process entail?

AHP is a multi-criteria decision making procedure that has been used to rank the various input layers that combined together constitute a means for mapping key variables related to contamination of groundwater by cholera and other water-borne diseases[1]. The AHP has a wide

[1] The Analytical Hierarchy Process was developed in the 1970s by Thomas Saaty and a wealth of literature is available on its theory and various applications. A concise summary of the process and its applications can be

array of applications including vulnerability assessments using GIS. In Zimbabwe, this approach has been used by Masocha et al. (2014) to develop a groundwater vulnerability map for Zimbabwe as part of a World Bank study on water quality in Zimbabwe (Murwira et al. 2013)[2]. This study used a similar approach.

The first step of the AHP process entailed normalizing all input layers with values between 0 and 1. After this initial step, all input layers were ranked against each other in terms of their relative impact on groundwater vulnerability. This is done by making a series of pairwise comparisons. The weighted inputs were combined in GIS to produce the output map (with weights ranging from 0 – 1). The input and output maps provide a spatially distributed description of cholera risk factors related to Harare's groundwater.

Summary of Input Layers

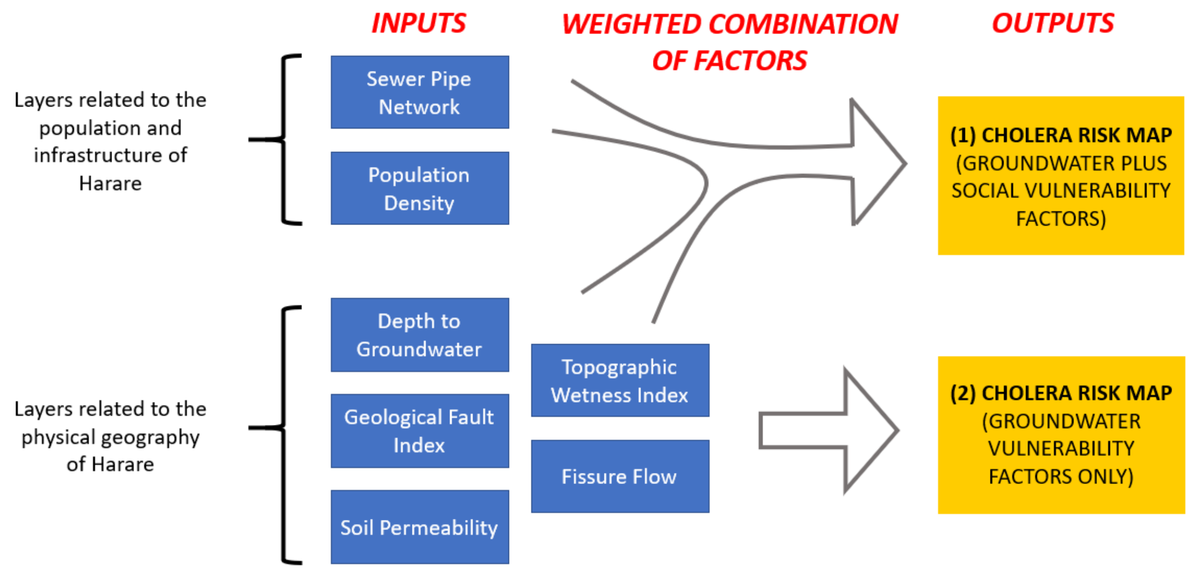


Figure 1: Schematic relating inputs and outputs

The list of data sources is provided below:

Data Layer	Source
Sewer Pipe Network	Provided by the World Bank team
Population Density	Facebook (https://data.humdata.org/)
Depth to Groundwater	Developed from a detailed geological map of Harare purchased from Knowledge Factory
Geological Fault Index	Developed from a detailed geological map of Harare purchased from Knowledge Factory
Soil Permeability	Developed from a detailed geological map of Harare purchased from Knowledge Factory

found in this article: Saaty, T.L. (2008) 'Decision making with the analytic hierarchy process', Int. J. Services Sciences, Vol. 1, No. 1, pp.83–98.

[2] A summary report of work by Masocha et al. 2014 is available at: http://documents.worldbank.org/curated/en/659751468196755638/pdf/103630-BRI-P126703-PUBLIC-ZWF-12-Watre-Quality-Nov-2014.pdf

Topographic Wetness Index	Created using a digital elevation model from Consortium for Spatial Information (http://srtm.csi.cgiar.org/)
Fissure Flow	Developed from a detailed geological map of Harare purchased from Knowledge Factory

(1) Sewer Pipe Network

Harare's aging underground pipe network is prone to blockages, burst pipes and leaks. The non-profit SMART Harare which tracks city wide service delivery received a total of 36 burst water pipe reports and 19 burst sewer pipe reports in 2018[3]. Burst sewerage pipes can leak into underlying aquifers, or into open faults in the city's geology or even seep into treated water pipes. We therefore viewed the piped sewer network as a risk factor contributing towards the transmission of cholera and other water borne diseases. It is worth noting that this an unconventional approach as a sewer system would ordinarily reduce risk of cholera.

Sewer pipe networks are mostly found in the high-density areas of the city to the south-west and also in the city centre. In order to map this risk factor, a 100m buffer was created around the sewer network. Areas within the buffer were weighted higher than areas outside the buffer in terms of Cholera Risk.

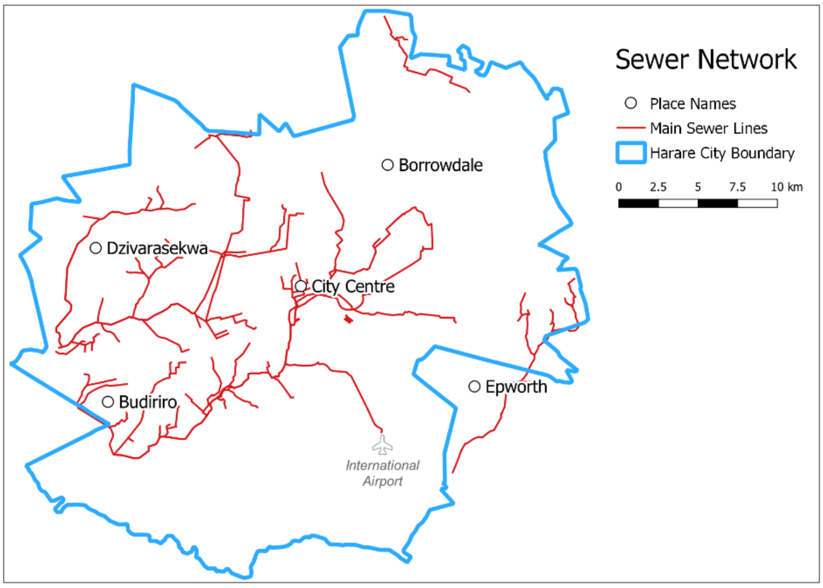


Figure 2: Harare's main sewer lines

Sewer Pipe Network	AHP Weight
Within 100m of a main sewer line	0.9
Outside of 100m of a main sewer line	0.1

[3] Historical service delivery reports are available om the SMART Harare website www.smartharare.org

(2) Population Density

Population density was related to cholera risk both in terms of the increased pressure on waste management systems and also the risk of the disease spreading quickly in a densely populated neighbourhood. High resolution (30m) population data from Facebook shown in Fig 3 below was used for the analysis. The data was resampled to 100m resolution and divided into quantiles which were weighted through the AHP pairwise comparison methodology.

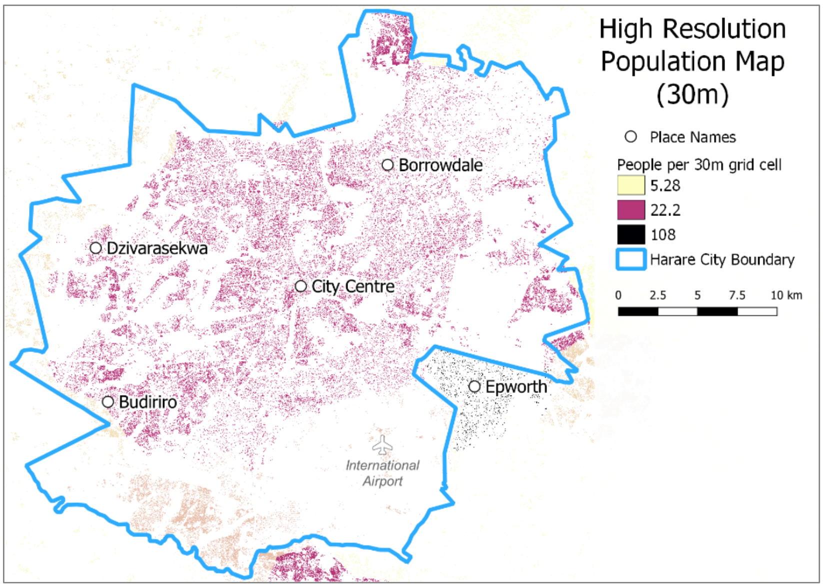


Figure 3: Harare population distribution

Population Density (people per 100m grid cell)	AHP Weight
<= 5.3	0.05
5.3 - 21.1	0.12
21.1 - 31.7	0.21
> 31.7	0.62

(3) Depth to Groundwater

Areas with shallow groundwater are more susceptible to contamination by burst sewer pipes or other contaminants entering the groundwater system. Pathogens, such as cholera and typhoid, are quickly attenuated in the unsaturated zone, but are much more persistent when they reach the groundwater zone. Shallow water tables significantly reduce the amount of time spent and the distance travelled in the unsaturated zone by pathogens, thereby increasing the risk of groundwater contamination. In addition, shallow wells are commonly dug and used at household level in high density suburbs as an alternative water supply to the erratic supply and mistrusted quality of Harare Water municipal water supply.

The mapped depth to groundwater (Fig 4 below) is derived from and based on the geological map of Harare - see appendix for details. Different weathering profiles are developed over different lithologies, and specific to Harare, granitoid quartzo-feldspathic rocks tend to develop duplex soil profiles with shallow perched water tables, which dominate the Upper Manyame Catchment to the southern, higher population density parts of the city. The mafic ferro-magnesian rocks develop deeper weathered profiles with deeper groundwater levels. These lithologies are predominant in the Mazowe catchment in the northern, lower population density parts of the city, where deep boreholes are more commonly used.

A limited number of groundwater depth borehole data was available from Médecins Sans Frontières (MSF). Although a detailed correlation could not be carried out because of the seasonal effects of the dates of acquisition, the clustering of the data and the limited numbers and spread of data points, a rapid visual “correlation” suggests that there is a groundwater level linkage to lithology and the shallower water tables do occur as shown in the map.

In addition, MSF data[4] for depth specific groundwater samplings in 2017 do show that the shallow groundwater (0-10m) is almost all contaminated with bacteria (19 out of 24 samples had streptococcus), while the deeper groundwater (10-50m) had 6 out of 50 samples with streptococcus, and the groundwater below 50m had 5 samples out of 26 with streptococcus.

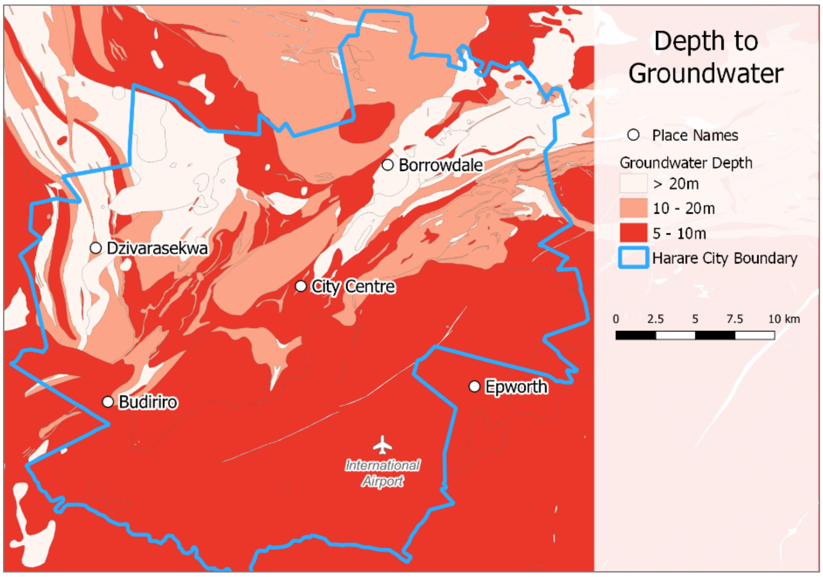


Figure 4: Depth to Groundwater

Depth to Groundwater	AHP Weight
< 5m	0.70
5 - 10m	0.15
10 - 20m	0.09
> 20m	0.06

(4) Geological Fault Index

Groundwater flow may occur as intergranular seepage, with water flow taking a torturous path through a granular matrix, or it may occur as rapid fissure flow through open fissures in the rock mass. Matrix seepage flow tends to reduce pathogen transport while open fissure flow may allow such pathogens to travel considerable distances.

Geological faults are planar features that tend to provide fissure flow pathways that would enable contaminated groundwater to flow rapidly over long distances. Since the fault zone represents the risk area, longer faults present a greater risk since they affect a larger area.

[4] The MSF study was carried out over a 2-year period (2016 – 2018) and findings are as yet unpublished

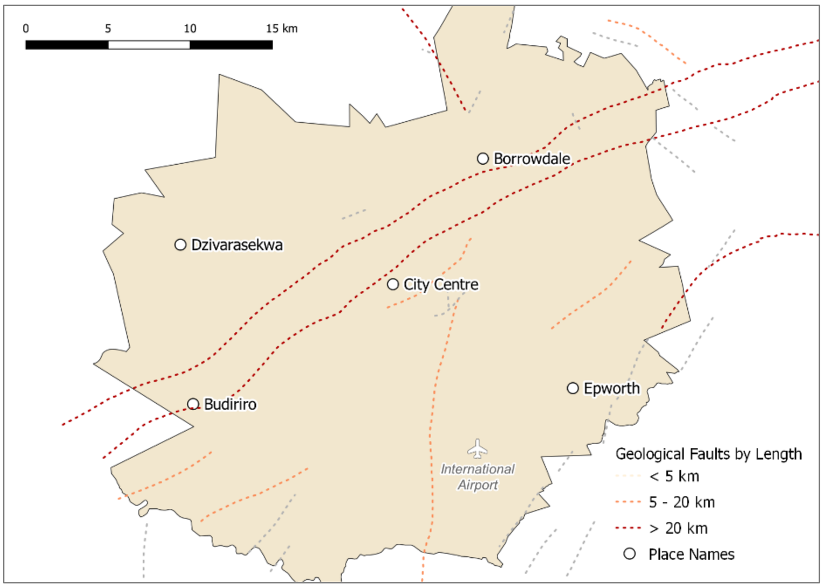


Figure 5: Map showing major fault orientation and length going through Harare

Fault orientation is also an important factor since it relates to the "openness" of the fault. The orientation of the principal compressive stress, σ_1 , in our region is from the north-east. Faults that are perpendicular to this σ_1 compressive stress tend to be "closed" under compression with reduced groundwater flow, while faults that are parallel to the σ_1 orientation tend to be "open" with greater groundwater flow. North-east oriented faults are forced open over time due to these prevailing stresses and present the highest risk for movement of contaminated water, while north-west oriented faults are closed and present the least risk.

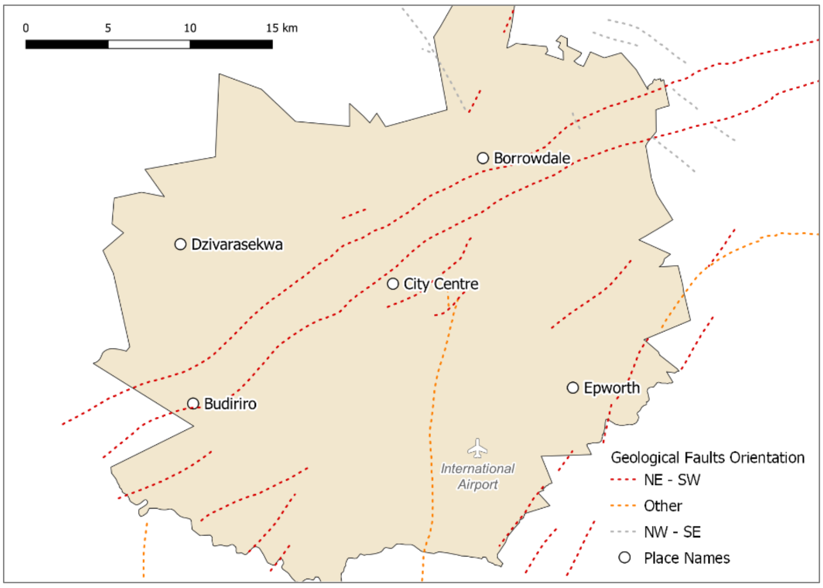


Figure 6: Map showing major fault orientation and length going through Harare

The geological fault index assesses both of these factors, fault length and fault orientation, with regards to groundwater vulnerability for pathogen contamination. Faults were put into 9 separate categories based on length and orientation and combined into a single fault map which was weighted using the AHP.

Category	Length	Orientation
1	< 5km	North-West
2	< 5km	North-South
3	> 5km and < 20km	North-West
4	< 5km	North-East
5	> 20km	North-West
6	> 5km and < 20km	North-South
7	> 5km and < 20km	North-East
8	> 20km	North-South
9	> 20km	North-East

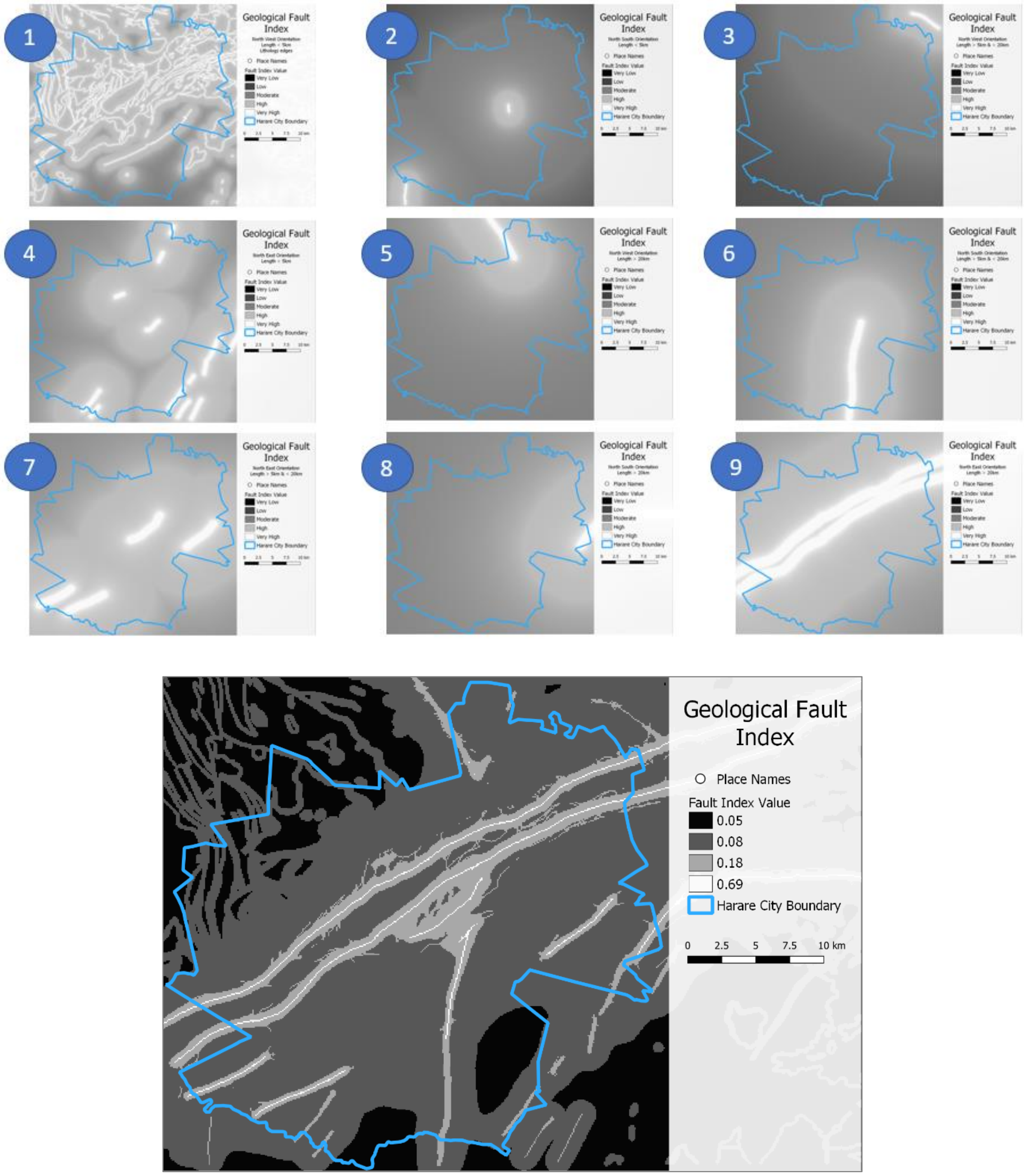


Figure 7: Geological Fault Index

Geological Fault Index	AHP Weight
0.0006 - 0.0063	0.05
0.0063 - 0.0230	0.08
0.0230 - 0.0647	0.18
0.0647 - 0.1335	0.69

The MSF study mentioned above identified some boreholes in Budiriro that occur along the Umwindsi shear / Greendale fault zone that were susceptible to contamination and repeated samplings of these boreholes showed high bacterial counts.

(5) Soil Permeability

Contaminated water will percolate more quickly and more easily through permeable soils down to the groundwater table. Heavy low permeability soils impede groundwater recharge and limit the amount of water reaching the groundwater zone. In addition, clay soils tend to adsorb contaminants further protecting the groundwater quality.

Soils are, for the most part, derived from the parent geological material. We used the detailed Harare geological map to develop a simplified relative soil permeability map. The quartzo-feldspathic granitic rocks were assigned the higher soil permeability values, while the ferro-magnesian basaltic rocks were assigned the lower soil permeability values. A detailed assignment of lithologies to soil permeability values can be found in the appendix.

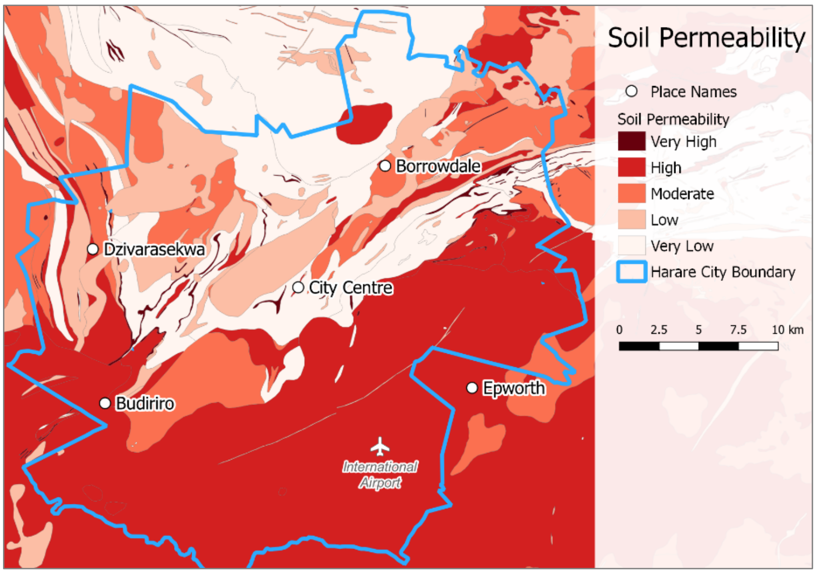


Figure 8: Soil Permeability Index

Soil Permeability	AHP Weight
Very High	0.53
High	0.26
Moderate	0.12
Low	0.05
Very Low	0.03

(6) Topographic Wetness Index (TWI)

TWI is commonly used to quantify topographic control on hydrological processes. The topographic wetness index is defined as:

$$\ln\left(\frac{a}{tanb}\right)$$

where a is the local upslope area draining through a certain point per unit contour length and b is the local slope in radians. The TWI has been used to study spatial scale effects on hydrological processes.

With respect to groundwater vulnerability, the TWI identifies areas where surface waters tend to accumulate thus facilitating groundwater recharge. Groundwater recharge is the principal driving mechanism that transports pathogens from the surface and shallow subsurface through the unsaturated zone into the groundwater zone.

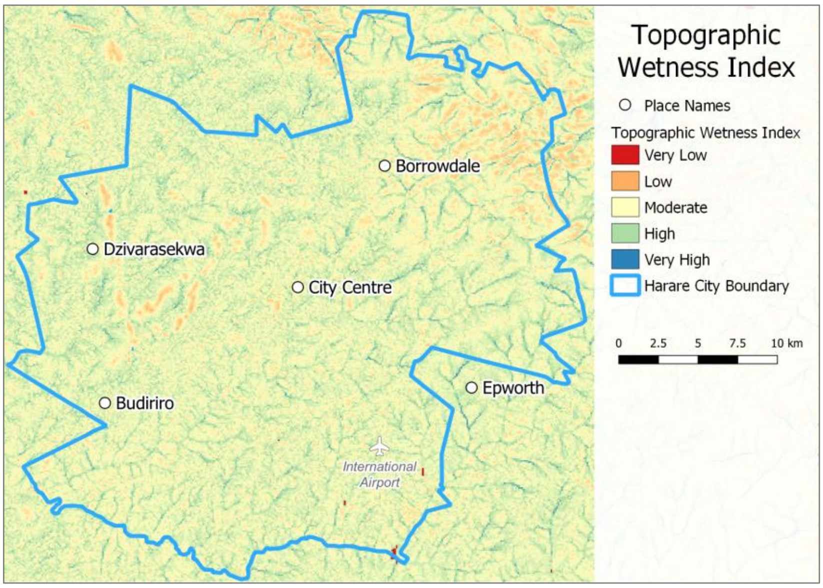


Figure 9: Topographic Wetness Index

TWI	AHP Weight
> 11.00 (Very High)	0.57
10.00 - 11.00 (High)	0.22
9.00 - 10.00 (Moderate)	0.11
8.00 - 9.00 (Low)	0.06
0.00 - 8.00 (Very Low)	0.04

(7) Fissure Flow

The difference between matrix flow and fissure flow has been described in the section of the Geological Fault Index, where it was indicated that open fissure flow is rapid, with little attenuation of contaminants and thus can transport pathogens over considerable distances.

We have used the detailed geological map of Harare to develop a fissure flow ranking. Rock types may be either more ductile or more brittle. Ductile rocks tend to deform by changing shape, by squeezing and by weathering into softer more plastic materials such as clays. These ductile rocks tend to be dominated by seepage matrix flow. Brittle rocks tend to be harder and respond to earth stresses by fracturing into blocky materials dominated by fissures and fissure flow.

In addition, fissure flow is also supported by rocks that are soluble in rain or groundwater, such as limestone and dolomite. These lithologies are well known for the development of "karst", consisting of open solution channels, caverns and caves. We have identified the brittle lithologies and limestone / dolomites in the Harare geological map and assigned high fissure flow values to these – see the appendix for details.

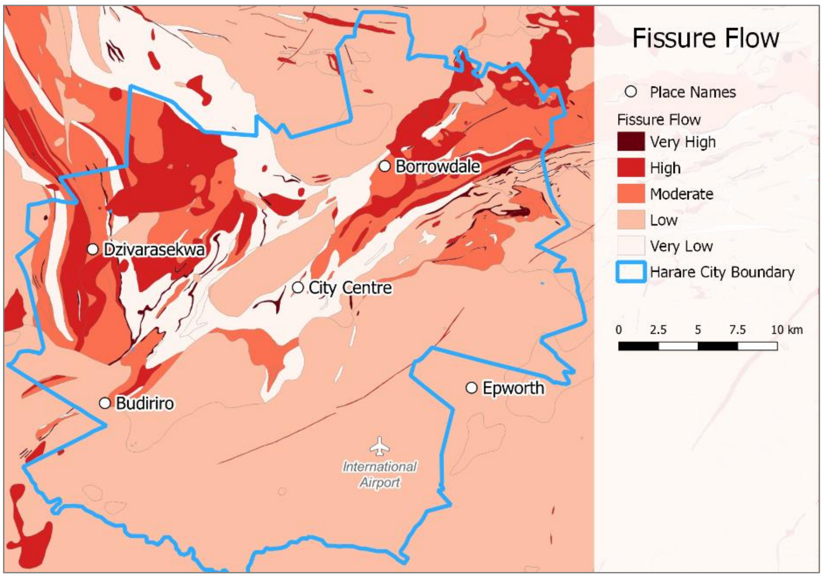


Figure 10: Fissure Flow

Fissure Flow	AHP Weight
Very High	0.56
High	0.25
Moderate	0.09
Low	0.06
Very Low	0.04

Final AHP Weights

The final composite AHP weights for the different groundwater vulnerability layers are given in the table below. These weightings are based on a pairwise comparison of each of the different factors against each of the others. Each pairwise comparison relies on individual judgement of the developer of the AHP, but there are protocols to ensure that there is a consistency in these decisions and a consistency index for the entire AHP is developed.

AHP table for Groundwater Vulnerability Factors Only – Model Output 2

In this AHP, those factors that promote rapid and widespread groundwater recharge have been allocated the highest weight; depth to groundwater and TWI between them account for 75% of the weighting. Faulting and fissure flow are local as opposed to occurring throughout the map and are given a combined weight of 17%.

Input Layer	AHP Weight
Depth to Groundwater	0.50
Geological Fault Index	0.13
Soil Permeability	0.09
Fissure Flow	0.04
Topographic Wetness Index	0.25

**AHP weights have been rounded to 2 decimal places for presentation*

AHP table for Groundwater plus Social Vulnerability Factors – Model Output 1

For the Cholera Risk AHP with the social and infrastructure factors, there is a different spread of weightings. It should be noted that there may be other significant factors, such as seasonal factors, access to treated water etc. and others. For the developed AHP, the combination of sewer lines, depth to groundwater and TWI account for almost 80% of the estimated risk.

Input Layer	AHP Weight
Distance to Sewer Lines	0.23
Population Density	0.06
Depth to Groundwater	0.38
Geological Fault Index	0.07
Soil Permeability	0.05
Fissure Flow	0.03
Topographic Wetness Index	0.19

**AHP weights have been rounded to 2 decimal places for presentation*

Summary of Outputs

(1) Cholera Risk Map (Groundwater plus social vulnerability factors)

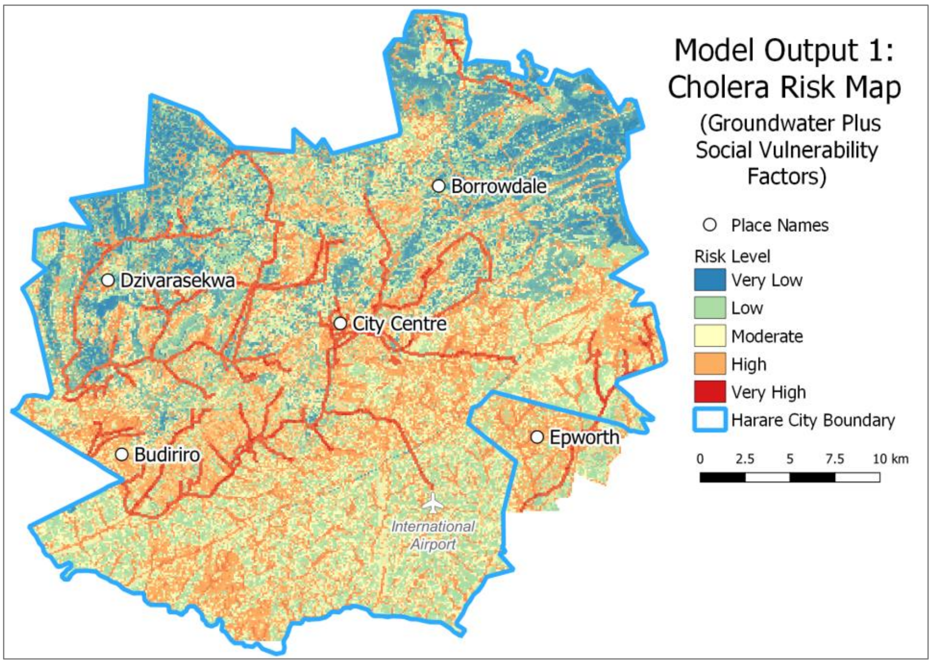


Figure 11: Cholera Risk Map with respect to physical and anthropogenic factors

(2) Cholera Risk Map (Groundwater vulnerability factors only)

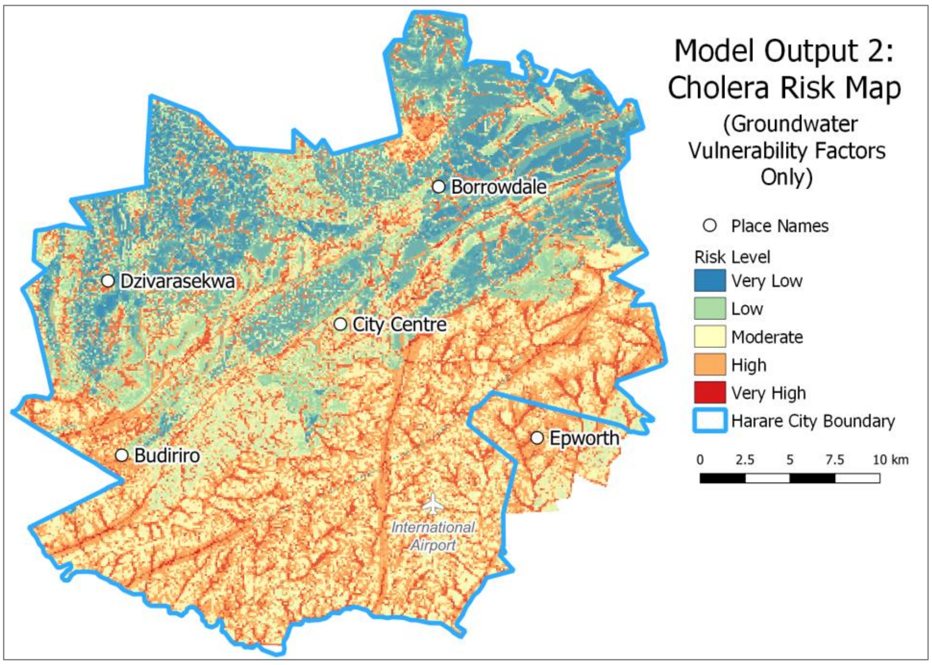


Figure 12: Cholera Risk Map with respect to physical factors only

Conclusion

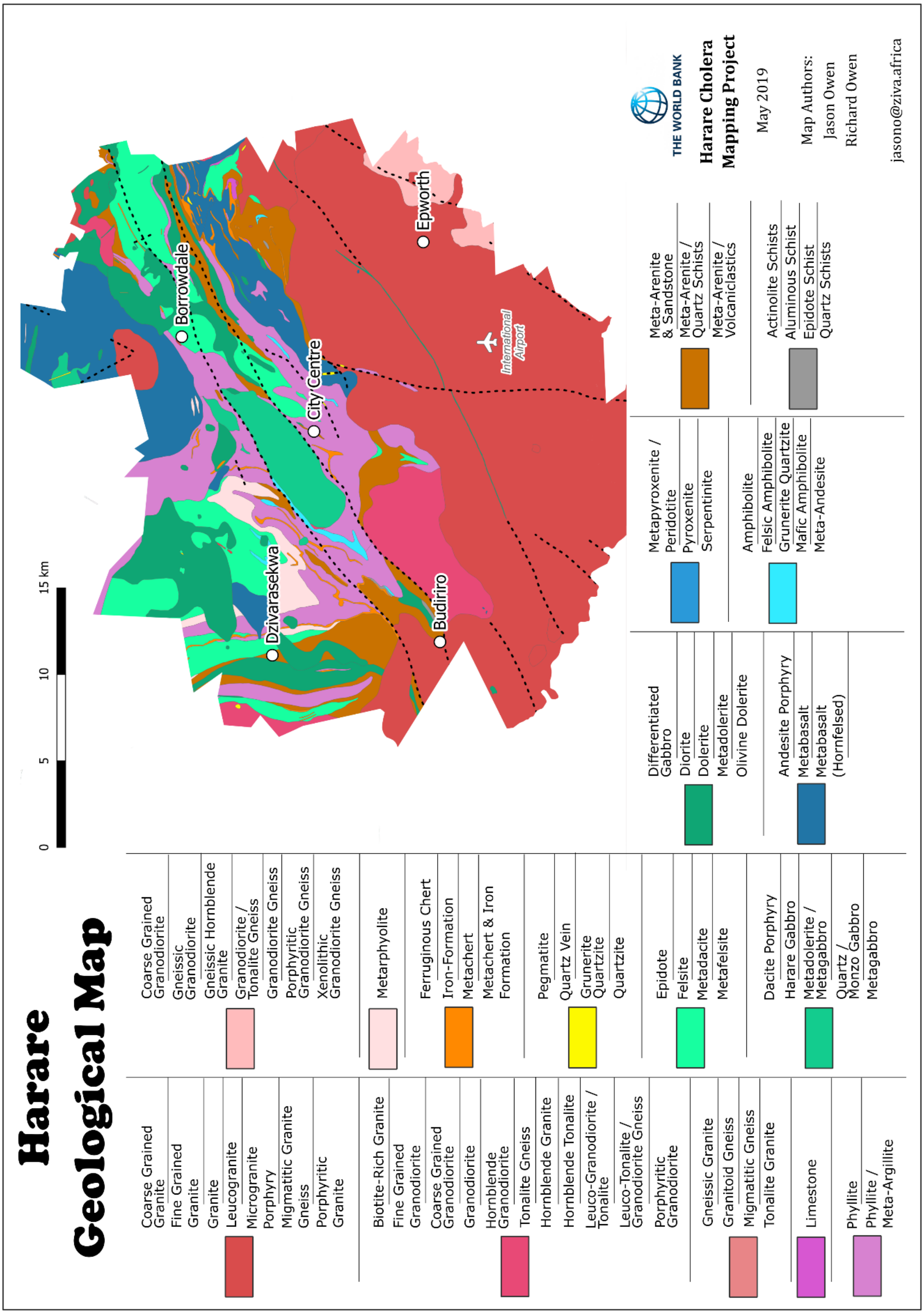
The developed maps and AHP analysis represent an “expert opinion” on the groundwater risk factors related to cholera in Harare. Weights may be adjusted depending on alternate hypotheses or new information. It is even possible to come to a consensus weighting through a group workshop with key stakeholders for example – which could provide an output that is widely accepted in the water and sanitation profession in Harare.

Some calibration was done by reviewing weighted maps against available data. For example water level data from ZINWA and MSF were overlaid and generally agreed with the depth to groundwater assessment. In addition, as indicated in the text, work done by MSF in their “WASH as Prevention” program did reveal that the shallow groundwater has a much higher bacteriological contamination and also that fissure flow associated with faulting appears to be a potential source of pathogen transport.

The outputs of this exercise provide some focus for appreciating Harare’s cholera risk in a spatial manner. It would be interesting to overlay actual case load on the risk maps in order to assess how well they may work as a predictor of cholera cases.

Appendix

Geological Map of Harare



Symbol	Lithologies
P	Limestone
R1	Coarse Grained Granite
	Fine Grained Granite
	Granite
	Leucogranite
	Microgranite Porphyry
	Migmatitic Granite Gneiss
	Porphyritic Granite
R2	Biotite-Rich Granite
	Fine Grained Granodiorite (FGR)
	FGR & Coarse Grained Granodiorite
	Granodiorite
	Hornblende Granodiorite
	Hornblende Granodiorite (HG) / Tonalite Gneiss
	HG altered to Hornblende Granite
	Hornblende Tonalite
	Leuco-Granodiorite/ Tonalite
	Leuco-Tonalite/ Granodiorite Gneiss
	Porphyritic Granodiorite
R3	Gneissic Granite
	Granitoid Gneiss
	Migmatitic Gneiss
	Tonalite-Granite, Massive-Banded Migmatite
R4	Coarse Grained Granodiorite
	Gneissic Granodiorite
	Gneissic Hornblende Granite
	Granodiorite / Tonalite Gneiss
	Granodiorite Gneiss
	Porphyritic Granodiorite Gneiss
	Xenolithic Granodiorite Gneiss
R5	Metarphyolite
O	Ferruginous Chert
	Iron-Formation
	Metachert
	Metachert & Iron-Formation
Y	Pegmatite
	Quartz Vein
	Quartz Vein & Pegmatite
	Quartzite
G3	Epidote
	Felsite
	Metadacite
	Metafelsite

Symbol	Lithologies
G2	Dacite Porphyry
	Harare Gabbro
	Metadolerite / Metagabbro
	Metagabbro
	Quartz / Monzo Gabbro
G1	Differentiated Gabbro
	Diorite
	Dolerite
	Metadolerite
	Olivine Dolerite
B3	Amphibolite
	Feldspathic Amphibolite
	Felsic Amphibolite
	Grunerite Quartzite
	Mafic Amphibolite
	Meta-Andesite
B2	Metapyroxenite / Peridotite
	Pyroxenite
	Serpentinite
B1	Andesite Porphyry
	Metabasalt
	Metabasalt (Hornfelsed)
BR	Meta-Arenite
	Meta-Arenite & Sandstone
	Meta-Arenite / Quartz Schists
	Meta-Arenite / Volcaniclastics
G	Actinolite Schists
	Aluminous Schist
	Epidote Schist
	Quartz Schists
	Quartz-Mica Schists
	Quartz-Sericite Schists/ Quartzite
W	Phyllite
	Phyllite / Meta-Argillite

Depth to Groundwater Classification

LITHOLOGY	EST. DEPTH
P	> 20m
R1	5 - 10m
R2	5 - 10m
R3	5 - 10m
R4	5 - 10m
R5	10 - 20m
O	10 - 20m
Y	10 - 20m
G3	> 20m
G2	10 - 20m
G1	> 20m
B3	10 - 20m
B2	10 - 20m
B1	10 - 20m
BR	10 - 20m
G	5 - 10m
W	5 - 10m

Soil Permeability Classification

LITHOLOGY	SOIL PERMEABILITY INDEX
P	High
R1	High
R2	Moderate
R3	Moderate
R4	Moderate
R5	Low
O	Very High
Y	Very High
G3	Moderate
G2	Low
G1	Low
B3	Low
B2	Very Low
B1	Very Low
BR	High
G	Low
W	Very Low

Fissure Flow Classification

LITHOLOGY	FISSURE FLOW INDEX
P	Very High
R1	Low
R2	Low
R3	Low
R4	Low
R5	High
O	Very High
Y	Very High
G3	Moderate
G2	Low
G1	High
B3	Very Low
B2	Very Low
B1	Low
BR	Moderate
G	Very Low
W	Very Low