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Investigation and Redesign of the Highway Stormwater Management System to Mitigate Gully Erosion, and Enhance Drainage Infrastructure Resilience; Case in Gokwe Town, Zimbabwe

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Abstract

This study evaluates the impact of land use changes on gully development and redesigning a highway stormwater management section in Gokwe Town, Zimbabwe, aiming to address gully erosion and enhance drainage infrastructure resilience, crucial for urbanizing watersheds and around highways. Using GIS processes, topographical profiles were derived; geotechnical lab investigations, and site hydrological assessments were conducted in evaluating the drainage system. Previous interventions failed to manage drainage properly to stop further erosion. The natural terrain slope, varying from 7.3% to 7.5% between 1985 and 2023, combined with highly cohesionless silty Kalahari sands (Ø=21.5°, c=8kN/m^2, permeability of 3.31×10^{-5}m/s), indicated high infiltration and low surface runoff under minimal human activity, increasing subsurface water drainage risks and soil collapse on the slope face. Urbanization increased runoff peak discharge (7.47m^3/s) as in 2023 due to ground consolidation, contributing to significant gully erosion. A trapezoidal channel network was designed to efficiently collect rainwater, reducing infiltration with additional drains. The redesign directed runoff to a detention pond, then down a slope drain to a gentler slope with finer soil particles. SWMM software modelling showed the system increased the collected runoff by 32%, reducing infiltration, erosive runoff on the soil and preventing soil collapse in sloping areas.

Keywords: Gully erosion, Stormwater management, Drainage, Kalahari sands, infiltration

Introduction

Managing infrastructure developments in areas with cohesionless soils has become increasingly challenging globally. This is due to the inherent erodibility of these soils and the potential for concentrated surface and underground water flows. Urban gullying has emerged as a significant global topical issue over the past few decades, with an average erosion rate of 2.4 t/ha/yr (Wuepper, 2020). Case studies from towns in Central Africa (Graham and Polizzotto, 2013) and Southern Africa (Rowntree et al., 1991) indicated that, the severity of urban gullying has reached alarming levels, affecting numerous towns and cities. Makaya et al. (2019) reported a staggering national figure of 400 million tons per annum of soil loss in South Africa due to soil erosion. In Democratic Republic of Congo, Rwanda, and Burundi, the total annual infrastructure damage is estimated at approximately US $267 million (Vandecasteele et al., 2010). This underscores the pervasive nature of urban gullying across the Central and Southern Africa tropical belt.

Urbanization often leads to increased stormwater runoff in the affected watershed due to the expansion of impervious surfaces like buildings, roads, and pavements, which reduce the capacity for water infiltration and deep percolation into the ground. These factors can lead to the rapid formation of deep, narrow gullies that potentially damages infrastructure, property, and the environment (Chikwue et al., 2023). In Zimbabwe, the designation of the Gokwe district as a town in 2007 led to a rise in human activity and infrastructure development, which in turn increased the amount of runoff from pavement and roof tops in the central business district. Due to the changes in growth, the drainage system has become inadequate to cope with the increased volumes of run-off. Additionally, the town's unique topography and climate, characterized by heavy rainfall, steep slopes, unpaved roads, and drainage channels, have exacerbated soil erosion leading to the formation of gullies. The existing deep Kalahari sand soils are also prone to urban gullying and are easily eroded by water and rainfall of any magnitude (Thomas, 2002).

The erosion of gullies in Gokwe pose significant risks to infrastructure, roads, and the surrounding environment. The underground infrastructure has been left exposed, the sewer pipes outfall is washed-out and manholes are hanging. Some of the gullies have been growing for more than six years, threatening to engulf the nearby residential homes as well as structures such as the Gokwe Magistrate Court and Zimbabwe Electricity Supply Authority (ZESA) offices. Additionally, access roads such as Gokwe–Siyabuwa road were closed due to threat to public safety, thus, vehicles heading to the district hospital and Siyabuwa neighbourhood had to find a different route in order to reach the facilities located beyond the ravine. Thus, the Town Council will need to set aside a sizeable sum of money for both internal and external intervention in order to reclaim land (Nanthambwe, 2010).

The loose and unstable characteristics of the soil in the Gokwe region makes it difficult for existing techniques, such as retaining walls and geotextiles, to successfully compart erosion. Culverts, roadside drains, and runoff redirection are some of the techniques that have been implemented to mitigate gully erosion. However, due to the unique geological properties of Gokwe, these have not proven effective. Redirecting storm water runoff into uncontrolled flows worsen erosion as it results in the damage of previously unaffected areas, thus, soil erosion continues to be a major issue affecting the ecological systems (Chapungu et al., 2023).

Considering the unique geological circumstances and the need for an efficient storm water management system, the aim of the study is to design of an effective highway sustainable storm water management system tailored to Gokwe's geotechnical and hydrological conditions, and recommend a method of gully reclamation for a specifically identified gully. The stormwater management system should efficiently capture and control stormwater runoff, preventing its harmful effects after the reclamation of the gully on the landscape.

Methods, Techniques, Studied Material and Area Descriptions;

Study Area Description

Gokwe town is situated within the Sedimentary Kalahari basin shown in Fig 1 characterized by loose, deep, unconsolidated sands (Zimbabwe Geological Survey [ZGS], 2021). These friable sands (Gokwe Formation) lack cohesive clay particles, making them easily erodible by water. The primary drainage system consists of ephemeral streams only flow during or shortly after rainfall events, but can cause significant erosion no matter the magnitude of the rainfall due to the loose sediment makeup (Gokwe Town Council [GTC], 2022).

The semi-arid climate experiences annual rainfall between 250-650mm, concentrated in the November-March period (Zimbabwe National Water Authority [ZINWA], 2023). Over 100 gullies have been identified within the Gokwe Town boundaries, highlighting the area's susceptibility to erosion (Nanthambwe, 2010).

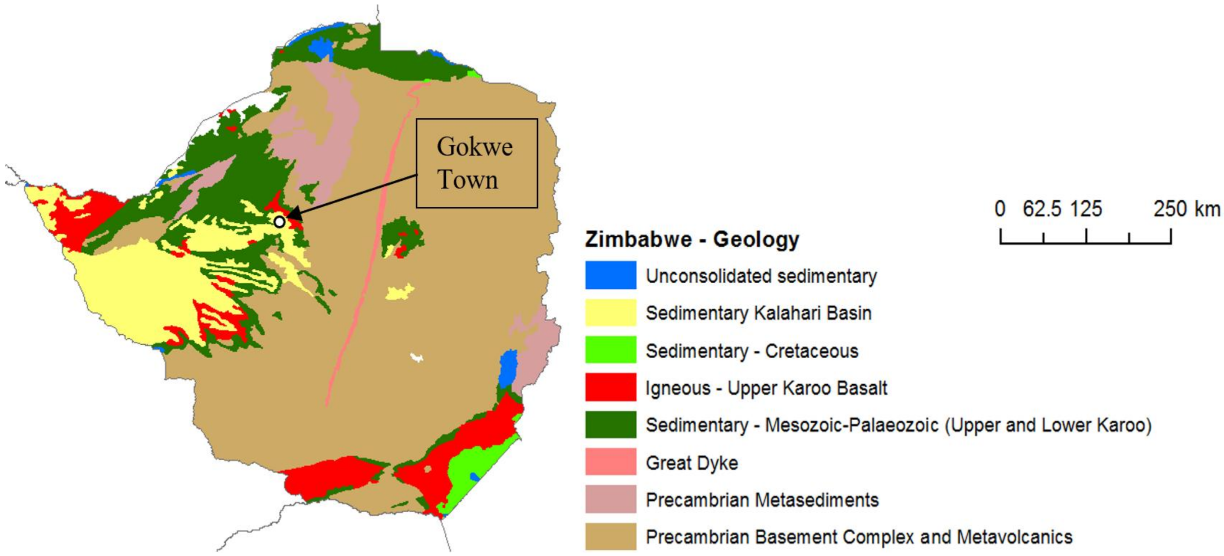

Figure 1: *Geological map of Zimbabwe showing location of Gokwe Town*

The town is located on a sloping plateau with radial drainage pattern directing water away from the central town area as shown in Fig 2. The developments have increased runoff on impervious surfaces from developments on a slopy face. The highly loose material found on the top of the plateau however keeps the infiltration rates high compared to runoff, hence no naturally defined river channels on the surface can be seen still unless it will be due to erosion.

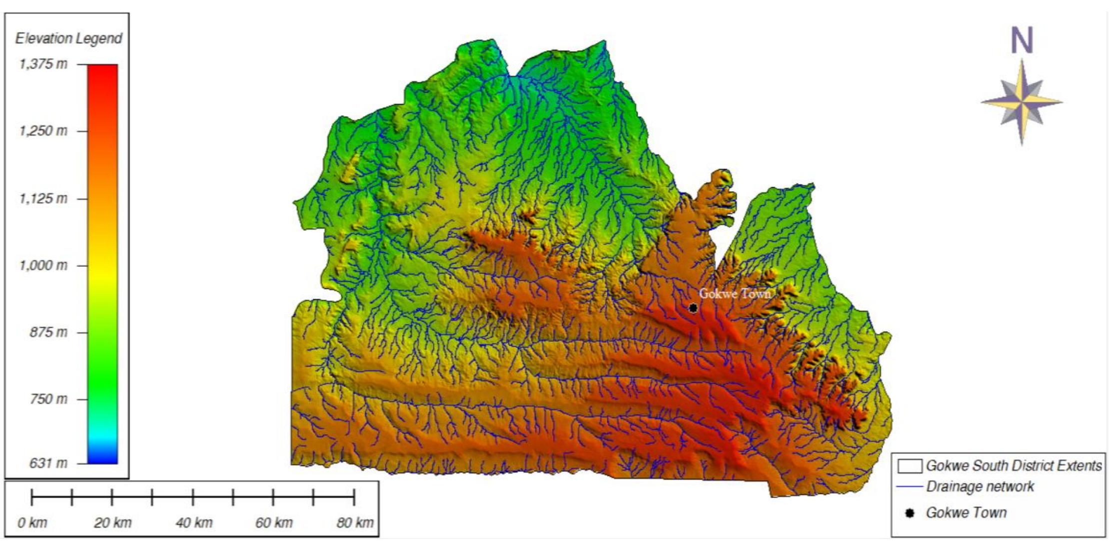

Figure 2: *Gokwe south district drainage network and Digital Terraine Model.*

The Green Valley area is affected by the gully known as gully No.3 within Gokwe town, it is predominantly on the naturally draining northeast of Gokwe town, where the old Nemangwe road passes through the area as shown in Fig 3. The majority of the township's drainage is collected by trapezoidal channel drains that are placed with stone-pitched pavement surfaces. Water collected in the trapezoidal channel drains is directed into the environment through a variety of cross drains through to Ruhwaya Village, which is located on the Eastern part of Gokwe town. Although poor maintenance is partly responsible for the system inadequacy, drainage capacity is the main contributing factor to formation of gullies.

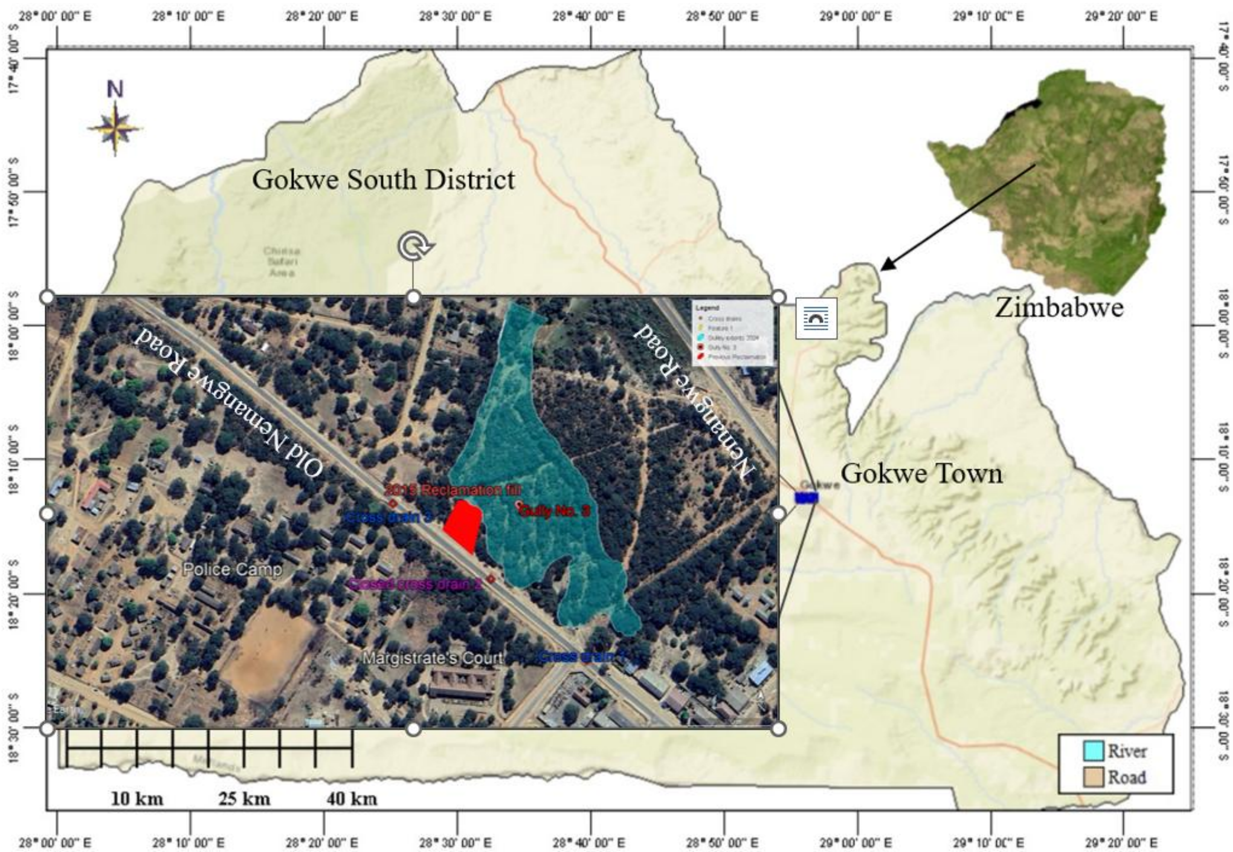

Figure 3: Zimbabwe, Gokwe South District and Gokwe town gully mapping.

Stormwater Management and Gully Formation

The data used for drainage system assessment was obtained from online sources and using on-site data collection methods. Identification of existing cross drainage infrastructure and measurements information was also obtained from the Ministry of Transport Midlands Province reports of the previous gully reclamation work done in 2015.

Satellite images of the town were obtained and processed for determining the catchment’s drainage pathways, watersheds and slope of the catchment area. The town’s developments and their effects on gully formation was also observed using satellite images and online sources. The images show the major changes in the growth of the gully channels with influence from the natural occurrences of rivers and drainage channels together with the developmental occurrences i.e., roads and drains. Runoff estimations and catchment area size was estimated for the undeveloped Gokwe town for the years 2005, 2015 and 2024; these were done from generating hydrology maps in QGIS and Civil 3d to analyse google world street maps for Gokwe town and using the online data sources for Terrain data (SRTM Worldwide Elevation Data (1-arcsecond resolution, SRTM Plus V3)), and DEM generation.

GIS and Data Processing

Land cover maps, slope maps and drainage maps were compared over time from 2005, 2015 and 2024 to determine the major changes on the gully attributed to the town’s development and urbanization. To process and analyse satellite imagery and Digital Elevation Model (DEM) geospatial analysis tools and software, including QGIS, ArcGIS, AutoCAD and Civil 3D as shown in Fig 4, were employed. GIS was used for processing of the satellite imagery and georeferencing them to ensure accurate spatial alignment. Using ArcGIS, georeferencing and image registration tools were utilized to align the satellite images to the UTM – WGS84 35S coordinate system. Contour lines were generated using ArcGIS's contouring functionalities augmented with coordinates and individual survey obtained on site for improved accuracy, facilitating the depiction of gully contours across different time periods. Hydrological analysis tools, including "Fill," "Flow Direction," "Flow Accumulation," and "Watershed," were utilized to delineate the watershed from the DEM and perform hydrological calculations. Civil 3D was utilized for terrain modelling and analysis. Longitudinal profiles were generated along the gully centreline to visualize and analyse changes in gully morphology over time for 2005, 2015 and 2024. Cross-sectional profiles were created at specific locations across the gully width, allowing for detailed comparisons of gully dimensions. The average yearly rainfall, the features of the runoff, and the period of flow concentration were all calculated using the hydrological data of the region. These techniques allowed for an in-depth evaluation of the gully's development and its correlation with the growth and urbanization of the area under investigation.

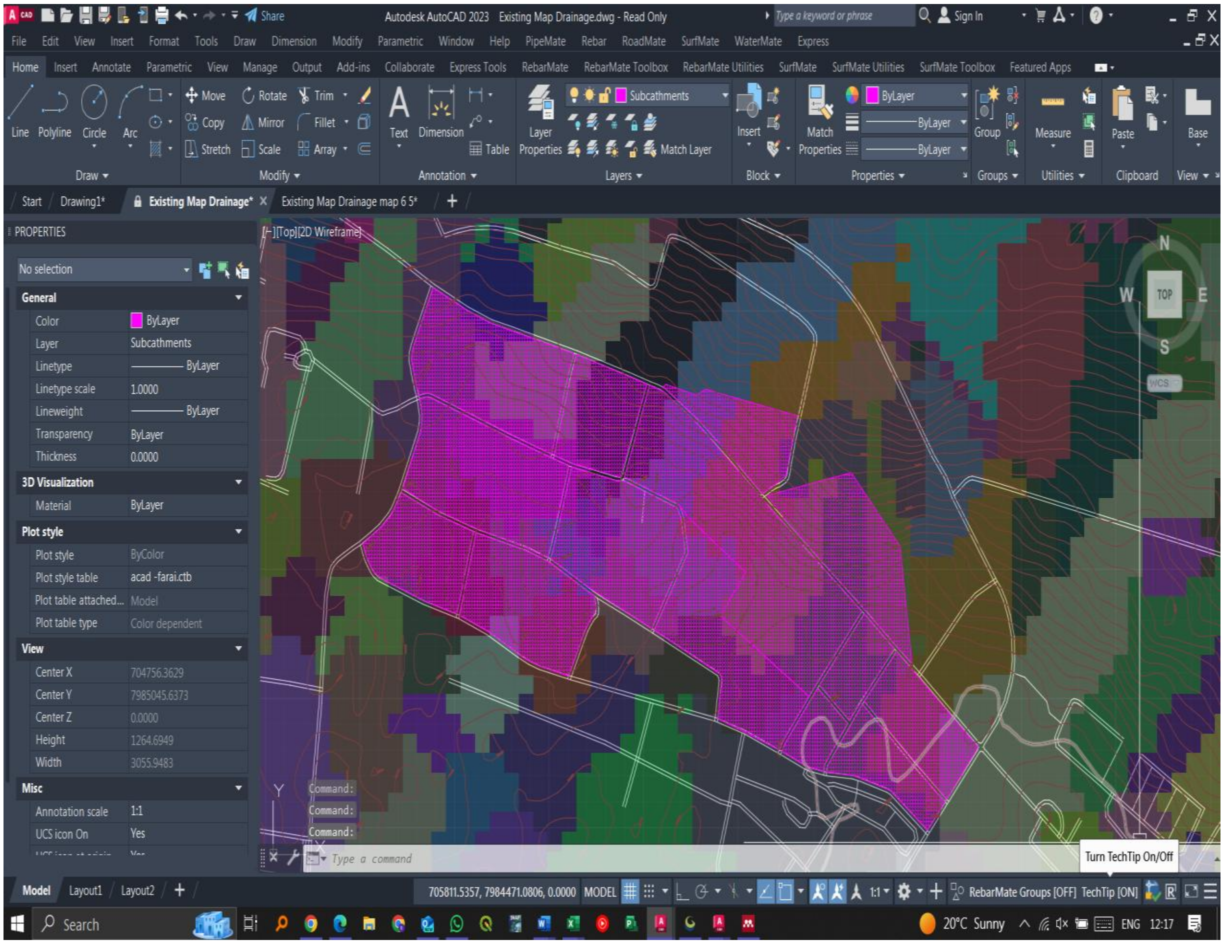

Figure 4: Data Processing and map creation in AutoCAD software

Soil Testing and Analysis

For the determination of soil properties and its behaviour in relation to gully formation and propagation, sieve analysis, Atterberg limits (plastic and liquid limit using Casagrande method), shrinkage limit, shear box test, and falling head permeameter test were conducted according to the BS codes of standards in soil testing. Infiltration characteristics of the soil and properties that influence the amount of precipitate absorbed into soils and runs off were determined.

Runoff Flow Estimations

The maximum discharge of the catchment was calculated using the rational method. It was then used to assess the capacity of the current infrastructure and to design the storm water management system in accordance with the Zimbabwean Sala Manuals of Highway and Stormwater Drainage Designs. Estimating the runoff rate that a channel structure can sustain safely is a crucial part of hydrologic design. The runoff rate, which is the time of greatest precipitation was computed over a five-year return period in this study.

The logical approach is the one used in the runoff rate computation design. The runoff coefficient (C) was based on the types of soil and land use, thus, a value of 0.55 was adopted (*Sala-Roads and Stormwater Drainage.Pdf*, 1990.).

Field Appraisal of existing drainage system

This information provided a basis for understanding the layout of the existing systems, including discharge points which were to be visited on site and observed to be unsafe and contributing greatly to the gully formation and backward propagation of the gully collapsing the drainage infrastructure as observed.

Feasibility and reclamation recommendation

The gully morphology was observed on site and images were taken, measurements of the gully dimensions were taken using manual methods with tape measure, electronic measuring tapes on camera and using Satellite imagery in QGIS and Google earth software packages.

Design of highway stormwater management system

For the redesign of the sustainable stormwater drainage, data collected during the assessment of the existing infrastructure, geology and topography and their influence to the development of the gully was then used in the design including the runoff calculated, rainfall intensity, catchment size, land use and drainage patterns mapping. The Manning's formula n value was obtained from the list of manning's surface materials as stated in the SALA manuals and the roughness coefficients. Detailed design drawings of the road sections could not be retrieved from the Ministry of Transport hence an estimation from the Design Manual of the Ministry of Transport Part F section 4.6 on Construction on Collapsing soils which covers Granitic soils and Kalahari sands was used.

Software Modelling using SWMM

The existing infrastructure was modelled using SWMM software and the redesigned system was also modelled and runoff, infiltration and flowrate discharges were compared for both systems.

Results

Assessment of the existing system

The study area was divided into distinct zones that contribute to runoff flowing towards the Green Valley gully as shown in Fig 5. This division enabled the description, analysis, and assessment of existing stormwater systems, including their condition, connectivity, and identification of deficiencies and potential improvements. The town's expansion has encroached upon natural drainage lines, resulting in runoff from roadways entering gullies and increasing infiltration rates. The current stormwater system consists of two drains and trapezoidal stone-pitched channels along the roadside, with runoff exiting at four points and flowing into natural gullies. However, one cross-drain is permanently closed due to its potential impact on gully development, as dischargea directly into a gully already threatened by road encroachment. Also see Appendix B and C.

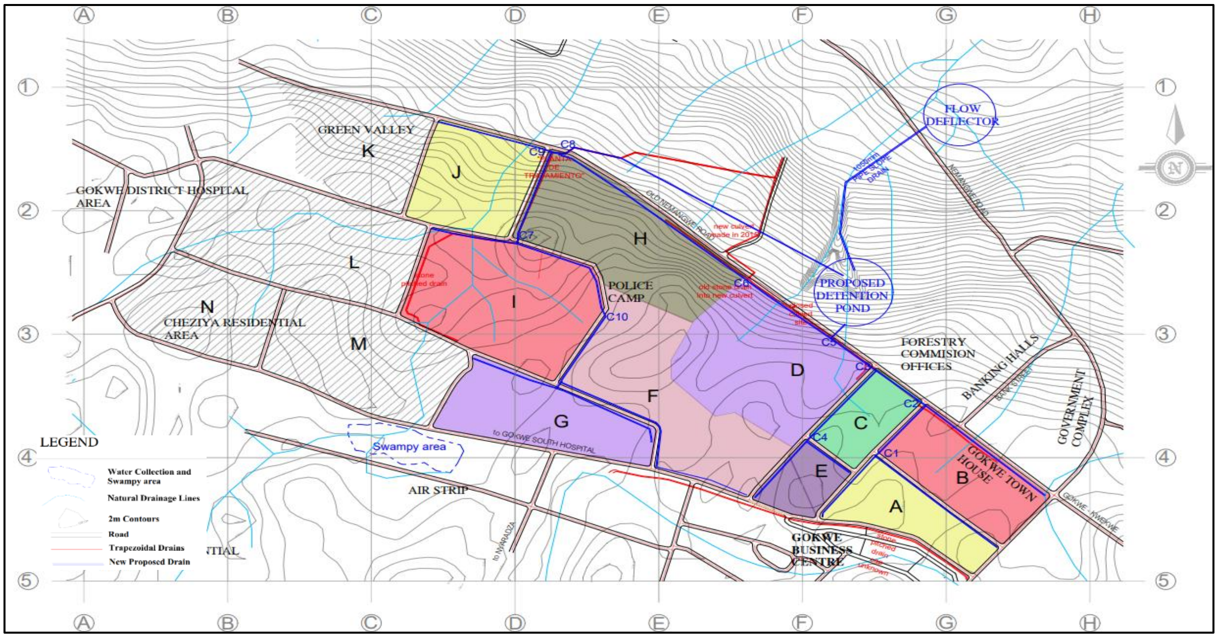

__Figure 5:__ Catchment Map distinct zones contributing to the catchment discharge.

Topography

The gully was found to be on a general slope of 7.56% as shown in Fig 6. The relationship between gullies and topographical factors as adopted from gully studies in China indicated that gullies are mainly distributed along the areas of steep slopes and ridges but have a threshold with a slope gradient of 10% - 30% (Castillo & Gómez, 2016). Zabihi et al. (2018) suggested, distance from river, drainage density and distance from the road effective factors for gully erosion. This provided useful information for the risk assessment and the design of gully treatment measures.

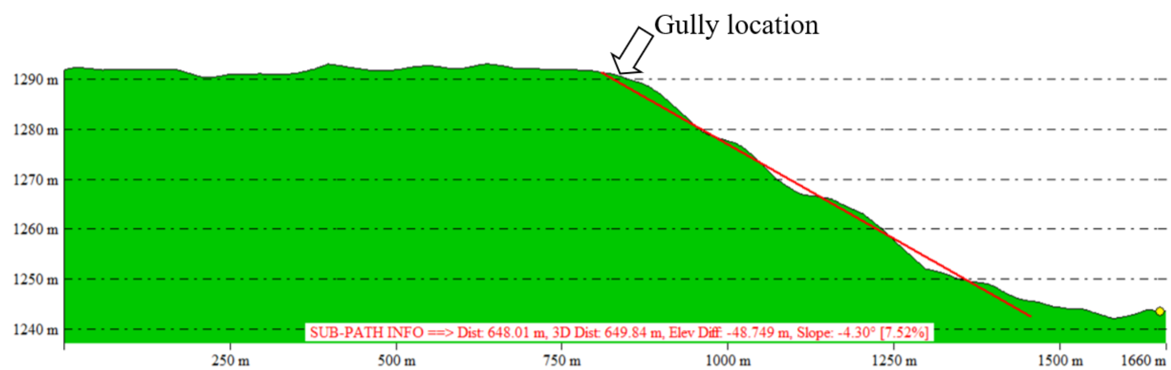

__Figure 6:__ Path Profile and slope extraction in QGIS across site.

Gully Profile Over Time

In order to demonstrate that the growth is not a typical drain channel for received precipitation but rather develops over time, with each rainfall event partially contributing to the gully development, the channel profile of the gully was found to accommodate a volume flowrate larger than would be practical given the rainfall intensity of Gokwe and greater than the accumulated runoff and area.

The pathways of the long section (green) and the cross section (purple) are presented in Fig 7, together with the area of focus and the location of the gully. The Green Valley area gully No.3, covered in vegetation as seen in Fig 6 expands approximately 60 meters long, 30 meters wide, and 5 meters deep. The gully's cross section and long sections, shown in Figs 8 and 9 illustrate how the gully has grown and changed over time. The yellow line depicts the gully profile in 2015, the red line shows the current gully profile as of 2024, and the green line shows the gully's invert level in 2005.

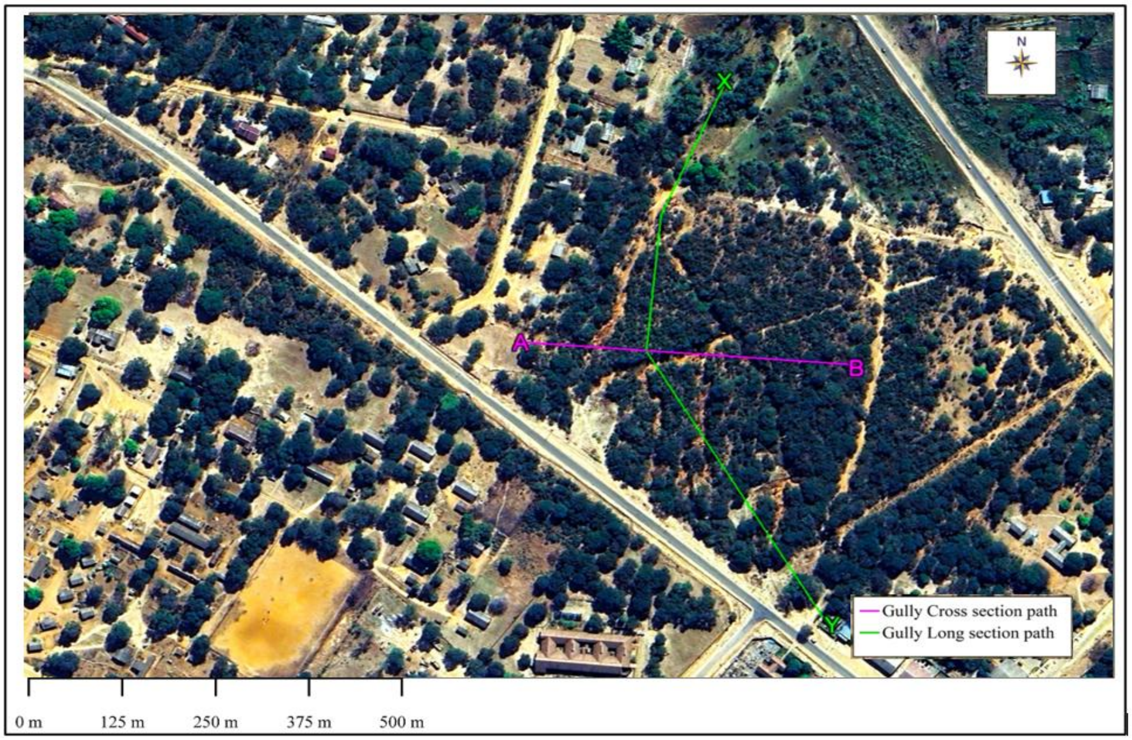

Figure 7: Study area image showing path of long section(green) and cross section (Purple) made in QGIS.

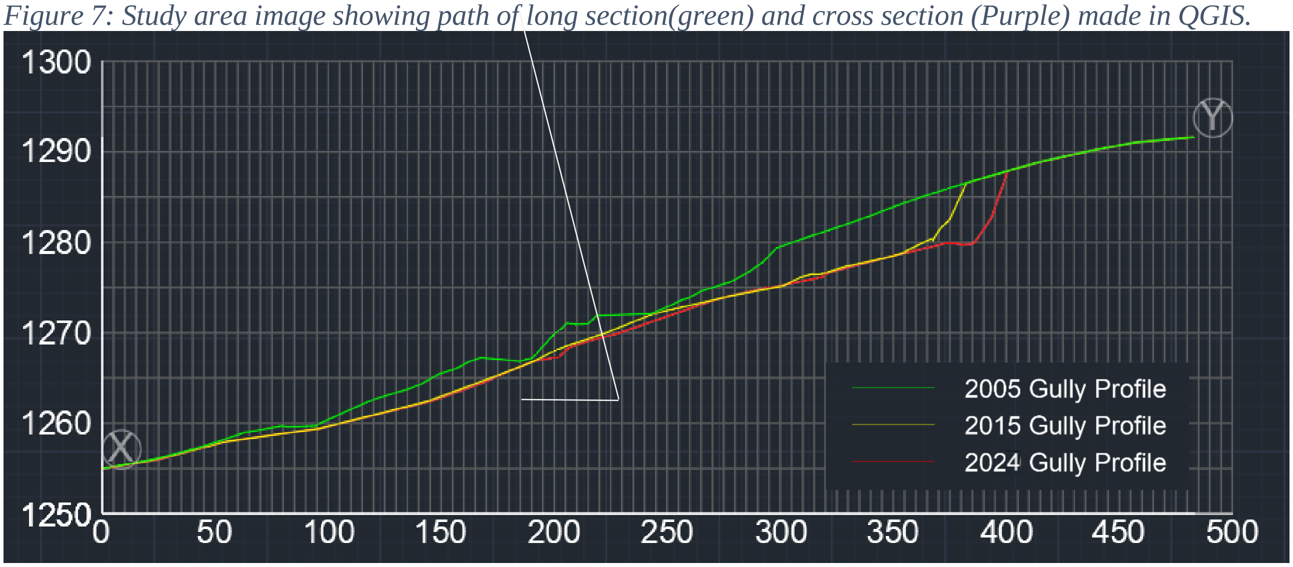

Figure 8: *Gully Long section over time as created in Civil 3D (units in meters).*

Figure 9: *Gully Cross section showing profile over time in Civil 3D (units in meters).*

Soil Tests

The sieve analysis, Atterberg limits, shear box, and falling head permeameter tests were conducted on the soil samples obtained from site. Particle grading tests as sieve analysis were carried out at 1m depth of the in-situ soil in the gully and at 4m depth, the two samples gave a similar grading. The particle size distribution of samples at 1m and 4m depth are presented in Fig 10. The fineness modulus of the soil was 0.61 at 1m depth and 0.30 at 4m depth, indicating a well-graded sand (SW) with very little or no fines. This classification implies that more than 50% of the soil's coarse fraction is smaller than the No. 4 sieve size. The soil's infiltration capacity and resistance to detachment and transportation by water are influenced by its characteristics, with high percentages of sands and silt making it more prone to erosion (Herrmann & Bucksch, 2014).

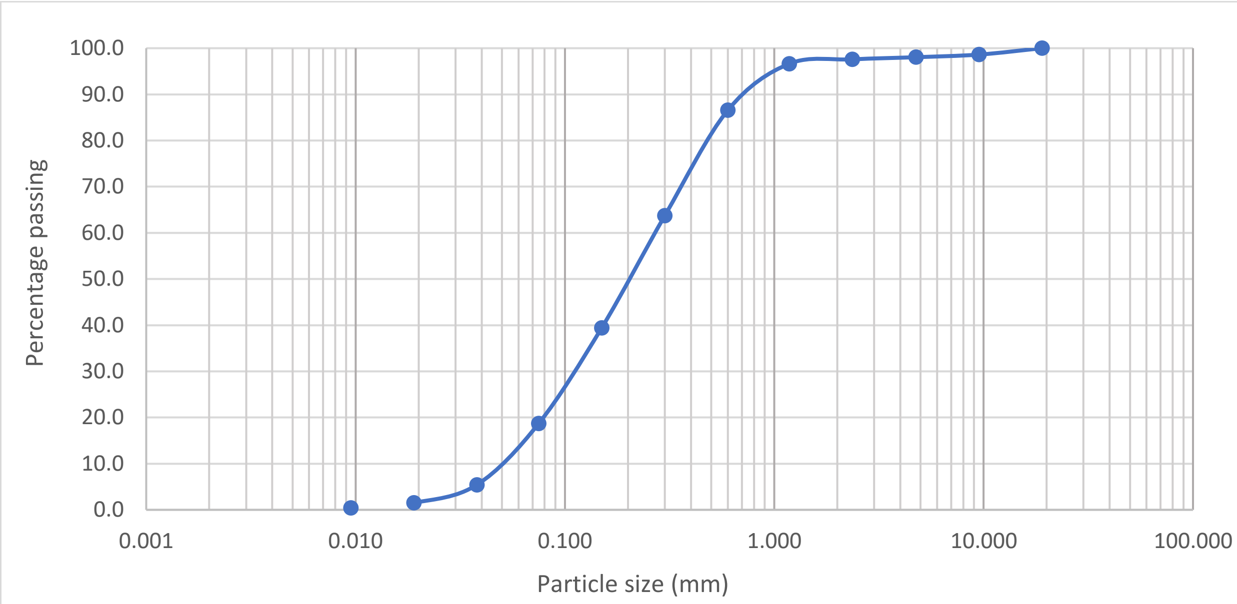

Figure 10: *Particle size distribution curve at 1m depth*

Atterberg limits

The Atterberg Limits testing for this soil sample provides crucial insights into its susceptibility to erosion and potential for collapsing. Significantly, the Liquid Limit (LL) could not be determined due to the non-plastic nature of the soil, indicating a complete absence of cohesive properties. This deviates significantly from standard values, where most soils exhibit some degree of plasticity (PI) with a corresponding LL and Plastic Limit (PL). The soil exhibited collapsing behaviour with less than 15 blows at lower moisture contents. This suggests minimal structural integrity and a high propensity to disperse and lose form when wetted. Standard Atterberg limits typically show a range of water contents where the soil exhibits plastic behaviour (between the PL and LL). The absence of this range in this sample signifies a highly unstable soil. Conversely, the soil fluidized (essentially turned into a liquid) with only around 5 blows at increasing moisture content. This indicates a rapid loss of strength and potential for liquefaction when saturated. Standard values for the Plastic Limit (PL) usually represent a higher moisture content where the soil retains some form. The observed behaviour deviates significantly, suggesting minimal ability to hold its shape even at moderate moisture levels. The absence of shrinkage further reinforces the lack of cohesive clays in the soil sample. Standard values for the Shrinkage Limit (SL) typically represent a distinct moisture content where further drying does not reduce the soil volume. No observed shrinkage suggests minimal clay content and a soil structure dominated by loose, granular particles.

Shear Box

The internal angle obtained was 21.5° and the value for the cohesion (c) found to be 8.40 kPa. The obtained angle is however lower than the typical range of 30-35° for loose, well-graded gravelly sands. The c value is significantly higher than the typical range of 0 - 5 kPa for loose, well-graded gravelly sands. The soil showed to have a higher cohesive strength which can be attributed to the presence of fine silt and a significant moisture content.

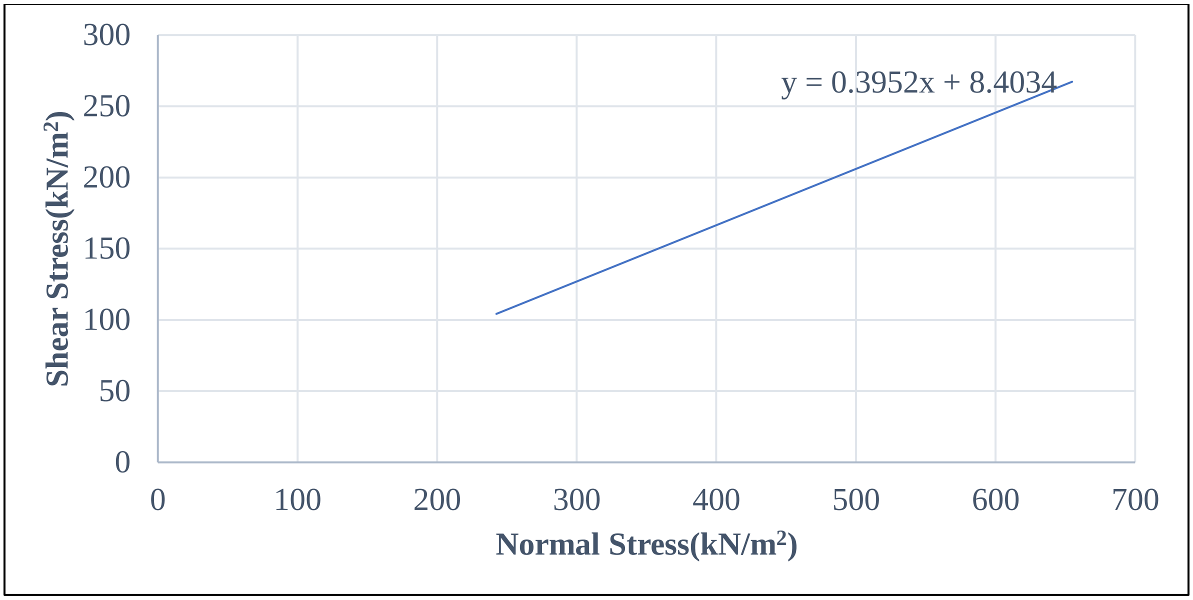

Figure 11: *Shear Box results graph from the lab tests.*

Based on the graph, the Shear Strength relationship of the soil at any given value of the normal stress would be: $\tau_f = 8.4 + \sigma_f \tan(21.5^{o})$

Falling head permeameter test

The obtained coefficient of permeability was $\boldsymbol{k_{av} = 3.31 \times 10^{-5}}$**ms^{-1}** The value falls within the range of high permeability according to (Herrmann & Bucksch, 2014), which is typical for gravelly sands with good particle size distribution and loose packing. This high permeability suggests that the soil will drain water quickly thus making the soil susceptible to erosion, especially if it is exposed to high rainfall or runoff.

Hydrological Analysis

Drainage patterns

Due to absence of natural waterways visible on the terrain, a large portion of the water is referred to as vadose water, which percolates underground to the phreatic. However, the water follows the hydraulic gradient rather than percolating downward, which causes the cohesionless soils in Gokwe to collapse as a result of seepage. There are no naturally defined river channels on the surface as a result of the increased runoff on a sloping terrain and extremely loose material, which causes the infiltration rate to be much higher than the runoff.

Design Considerations and Assumptions

The following design parameters for trapezoidal channels were used in order to maximize hydraulic efficiency and stability, as well as to choose the type of lining material for the channel that will serve as the foundation for choosing Manning's roughness coefficient, n, which has a value of 0.017. The freeboard of the design depth was designed to be above, d (20%), the side slope, Z = 1:3, the bed slope value, S = 0.0002, the minimum allowable velocity to prevent siltation (V), and the maximum allowable velocity to prevent scouring (V) (Sala-Roads and Stormwater Drainage, n.d.).

Developmental Occurrences

From the investigation on the growth of the gully it was observed using Google earth and aerial imagery that from before, the gullies in Gokwe further developed at a faster rate as the town developed over time and not as it used to be before 1980.

Flow estimation and field appraisal of existing infrastructure

By applying the aforementioned techniques, the maximum flow that could be achieved in the focal drain's existing drains was 1.6 m^3/s. This result was compared to the drain's capacity of 1.38 m^3/s. Appendix C has a tabulation of the systems' component evaluations, the drains and the existing system details as provided in the GIS platforms and observed. Along with the flow accumulation maps created in GIS programs, the primary natural drainage lines and sub-catchment ridgelines have also been represented indicatively on the maps. These are based on contours and DEM created using QGIS and Civil 3D.

The drainage catchments are all interconnected with the single drain discharging to individual discharge points across the road and into natural gullies on the slope faces. The following are the key issues with the current systems:

i. Gully erosion whenever the channel drain lets the water into the natural environment and leading to collapse of the drainage structures going upstream as the underlying soils collapse towards the road; and
ii. Erosion on some of the steeper gravel roads (like the road branching from the main road of study and on the right).

The key drainage improvement opportunities for the system include upgrading of undersized driveway culverts, and reducing the load on the overall system by provision of cross culverts discharging to stable or protected slopes through slope drains since the slope and soil type are never favourable to runoff generation. Figure 12 shows the existing drain on site which was used to determine the estimated flow capacity.

Figure 12: *Size estimation of the existing drain on the side of the road adjacent to the gully.*

Table 1 shows the capacity and level of operation of the existing drain. The 120% drain discharge indicates how the existing drain has become insufficiently small for the generated runoff as should normally be leaving a freeboard of around 20% (Specialist et al., 2006)

Table 1: Estimated drain capacity of existing draining along the road

Description	*Symbol*	*Units*	*Value*
Drain depth	D	m	0.4
Top width	Wt	m	1.2
Bottom Width	Wb	m	1.2
Slope	S	Ratio	0.013
Manning's n value	N	$s/m^{1/3}$	0.015
Sectional Area	A	m^2	0.48
Wetted Perimeter	P	m	2.00
Drain full Capacity	Q	m^3/s	1.38
Drain Full Capacity Velocity	V	m/s	2.9
Drain full Capacity	Q_{full}	l/sec	1381.7
Runoff discharge	Q	l/sec	1655.86
% Drain full	$Q_{full\%}$	%	120

Gully Mitigations Measures

Retaining wall, gabion structures and geotextiles were found to be the most common methods used for gully reclamation. The site has been previously reclaimed by gabions and concrete surfacing. The proposed designed system will comprise of trapezoidal channels that drain into a detention pond and then downslope through an underground slope drain circular channel. This is adopted from the stormwater management systems in Ontario, Canada and Nigeria. The detention pond utilizes the gully volume already in order to reclaim the gully and prevent further expansion at the same time.

Discussion

Overall, the geotechnical analysis reveals a soil susceptible to erosion, with high permeability and potential for rapid drainage. The soil's lack of cohesion, tendency to collapse, and absence of a plastic range indicate high erodibility and instability. This soil is prone to slope instability, sudden failures, and piping failure, which can lead to the collapse of foundations or supporting structures. Mitigation strategies are necessary to address the soil's inherent instability.

If infiltration stays high, this soil poses a serious risk of piping, a condition in which upward seepage pressure exceeds the earth's downward weight. This results in the soil losing its shear strength and acting more like a liquid, which may cause pipes to form inside the soil. The collapse of supporting structures or foundations can be caused by piping failure.

Although the overall appearance of the soil is the same across a range of around a kilometre, the size of the samples for laboratory tests was very tiny, making it unsatisfactorily representative in soils with considerable macrostructure characteristics. Furthermore, because of the loose soils at the location, it is challenging to collect samples that are genuinely undisturbed and to replicate in a lab the actual flow and stress conditions found in the field. The relative abundance of mega-gullies in the area where urbanization has surged over the last 15 years serves as evidence of this.

Design of stormwater management

Trapezoidal Drain Design

The drains were of varying sizes as included in the full drains schedule in the Appendix D. The largest being of dimensions 450×750 trapezoidal channel with side slopes of 1:3 and concrete lining as presented in Figure 13.

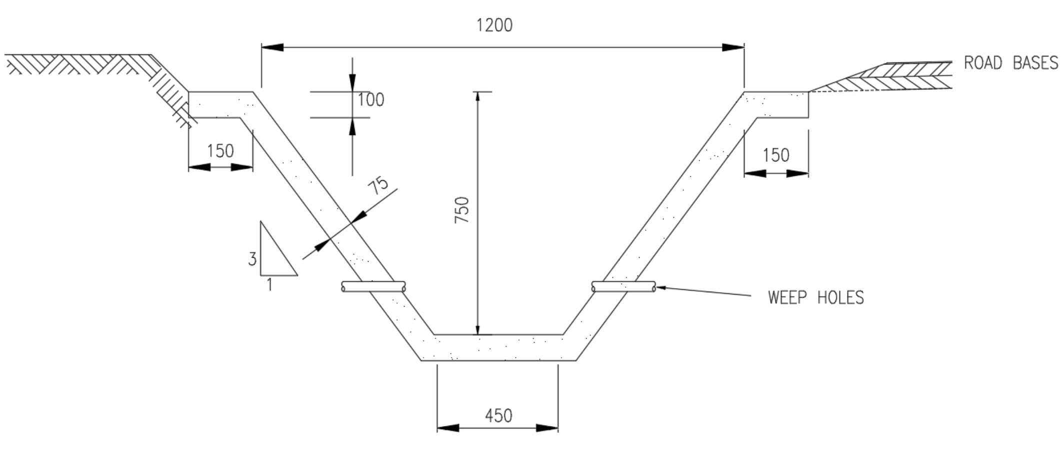

Figure 13: *Trapezoidal Channel Cross section (by author).*

The trapezoidal open channel was selected for this design. It can stand and resist flood and erosion problems for the catchment area.

Culvert Design

Annual Rainfall = 500mm
For high density Areas, used C = 0.8

For low density, used C = 0.4
Assuming a 3-year and 5-year flood return period as shown in Table 2.

Table 2: Discharge Calculations using the Rational Method.

AREA	*L (m)*	*H (m)*	*N (yrs)*	*R (mm/yr.)*	*C (N/A)*	*Area (ha)*	*T (min)*	*I (mm/hr)*	*Q (m^3/s)*
A	285.27	2	5	500	0.8	2.82	10.23	131.18	0.82
B	308.36	1.5	5	500	0.8	3.73	12.50	122.00	1.00
C	295.87	2.3	5	500	0.8	1.91	10.11	131.70	0.56
D	228.91	6.2	5	500	0.4	6.82	5.13	157.79	1.19
E	123.32	1.5	5	500	0.4	1.47	4.34	162.94	0.26
F	479.29	3	3	500	0.4	6.52	15.94	97.70	0.70
G	237.03	2	3	500	0.4	4.43	8.26	124.24	0.61
H	453.98	15	3	500	0.4	6.46	8.06	125.15	0.89
I	328.89	2	3	500	0.4	7.07	12.06	109.52	0.85
J	266.50	10	3	500	0.4	3.83	5.09	139.94	0.59

The storm water drainage was designed to cater for 5-year design floods. The Rational and Colebrook together with the Manning's formulae were used in the design of the drains and culverts. Storm water drains and culvert sizing included in this report in Appendix D. The most important things to address would be making sure that the cross drains on the road do not discharge into natural gullies and existing in-situ material, and that discharge flow pathways are provided to stable slopes.

Detention Pond

An irregular shape of detention pond was designed to hold a volume of **23,92m^3** storage volume as determined and shown in Fig 14. Figure 15 also includes a layout of the designed pond as drawn in Civil 3D. The detention volume estimated by the Modified FAA Method for:

- Area = 167.5acres
- Runoff coefficient = 0.8
- Time of Concentration = 35min
- Return Period = 5years
- Using a maximum allowable release rate (MARR) of 40% = 0.4 x 7.47

= 2.99m^3/s
=105.5ft^3/s

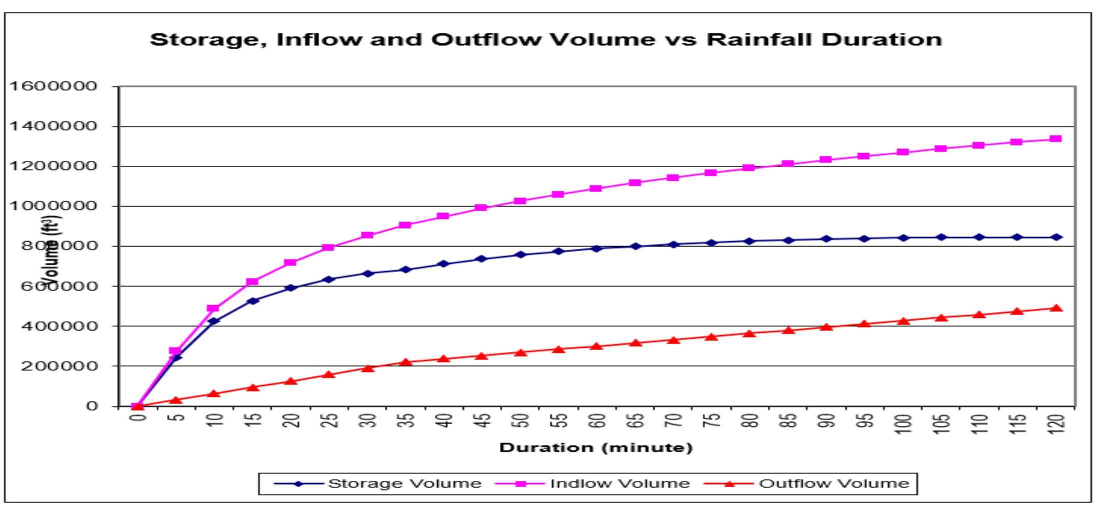

Figure 14: *Storage, Inflow and outflow volumes vs Rainfall duration.*

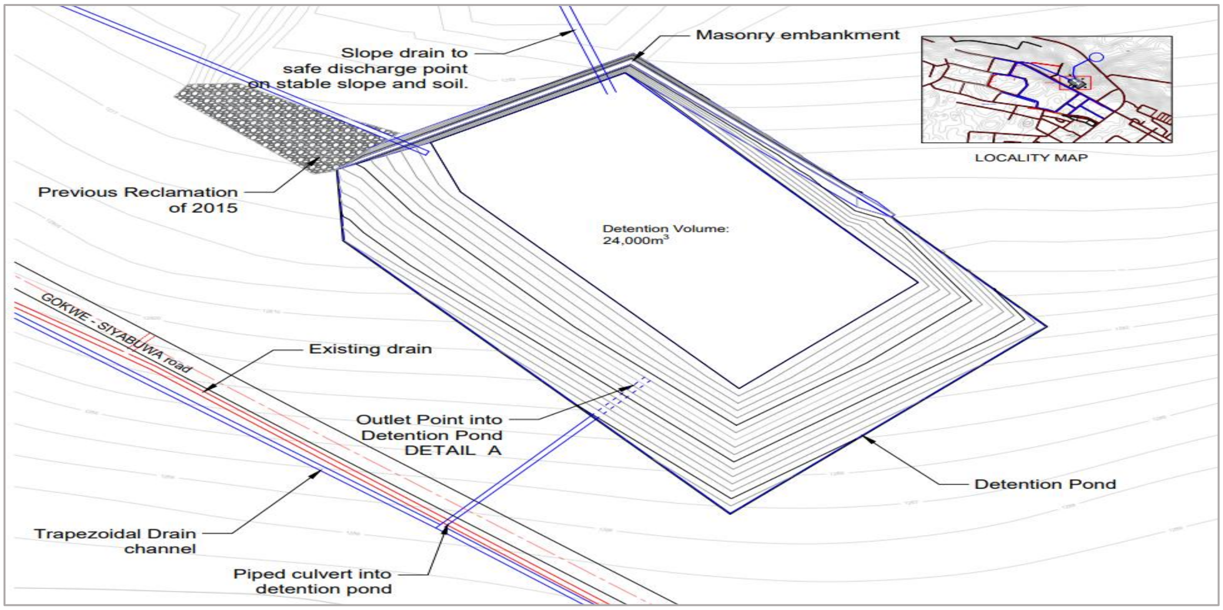

Figure 15: *Detention Pond Layout*

Slope Drain

A piped slope drain of size 1050 mm was designed to drain the stormwater from the detention ponds.

SWMM Model

An estimated 3-hour intense rainfall time pattern was used to run a computational model of the current system, as would be expected in a 5-year return period. The total amount of runoff created increased by 31.6%, from 16,740 m^3 to 22,041 m^3. Figure 16 and 17 show the existing and new system modelling images, respectively, showing the infiltration, volume flowrate and the velocity indicators. When the new network of drains was added, the peak runoff was measured in relation to the system output peak runoff and revealed a considerable reduction in infiltration.

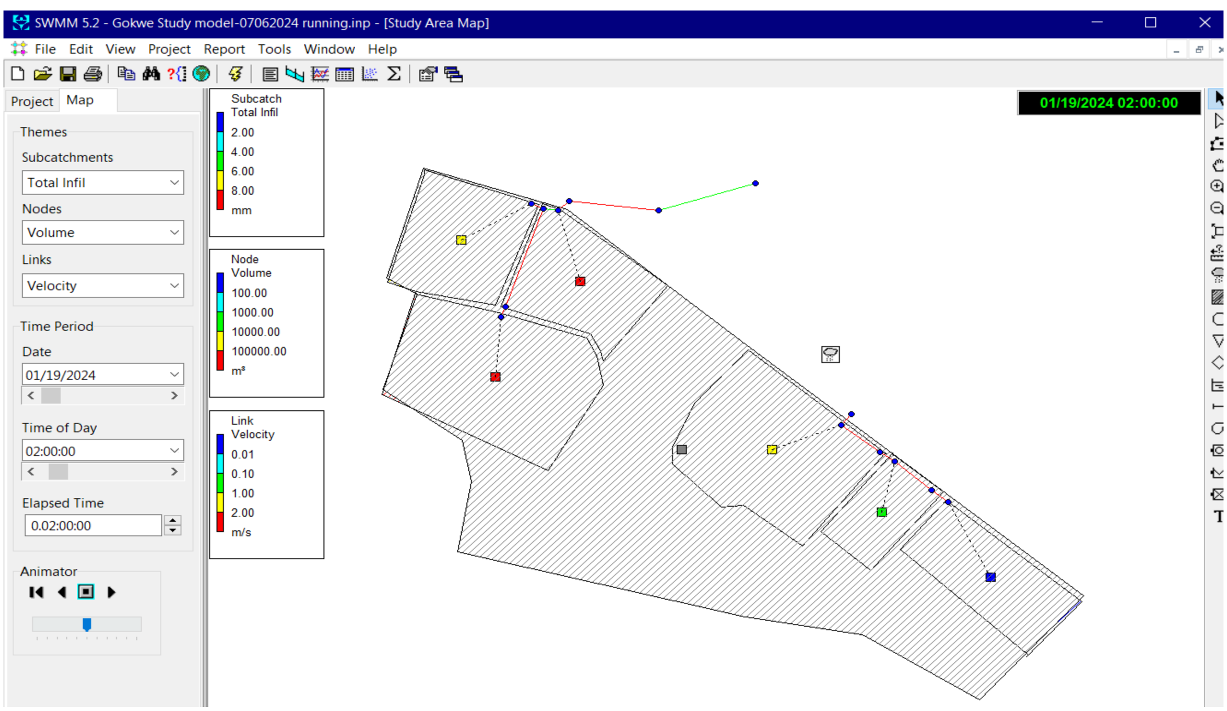

Figure 16: *Existing system modelling in SWMM.*

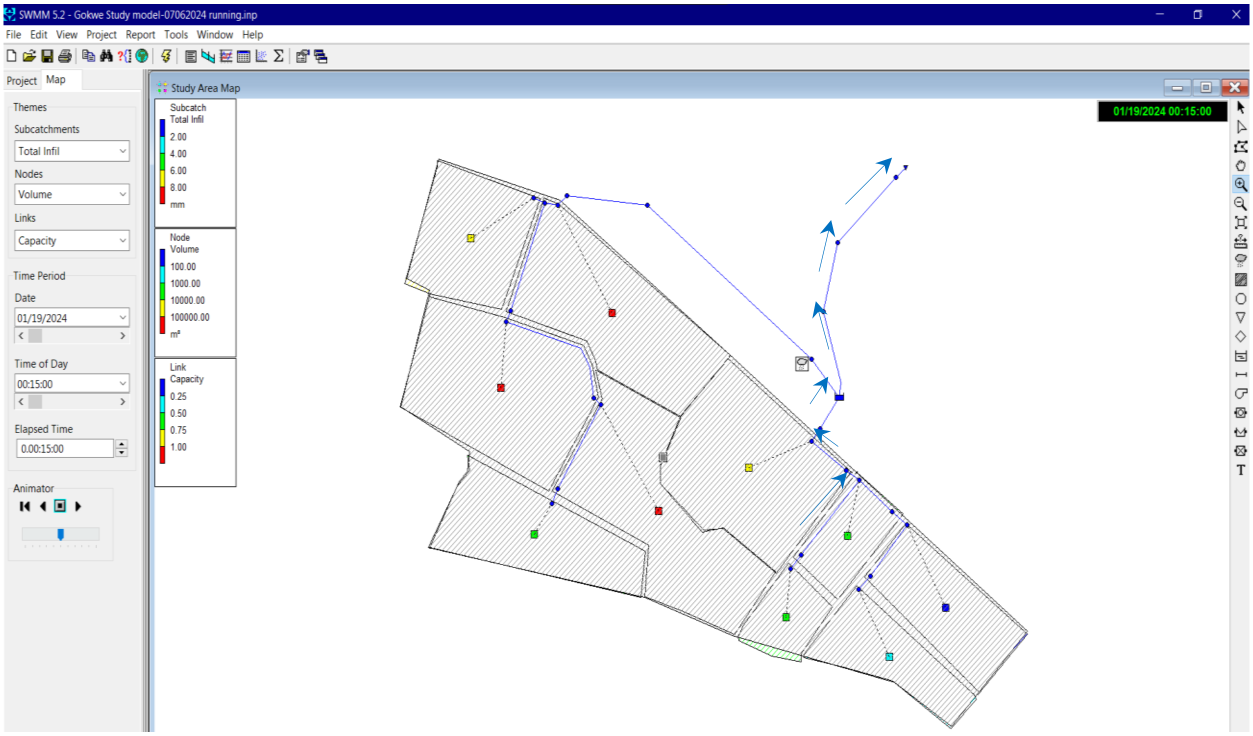

Figure 17: Designed system modelling in SWMM.

Incorporating the new system and further dividing it into smaller catchments proved to increase the overall outflow from the system and ultimately leads to an increased total discharge to indicate a reduction in the infiltration rates, assuming the rate of evapotranspiration has not decreased significantly as all other factors remain constant. This is illustrated by the new system graph (orange) on top compared to the existing system graph (yellow) in Fig 18. The graph's blue and green lines represent the water's depth per unit of time that it leaves the system together.

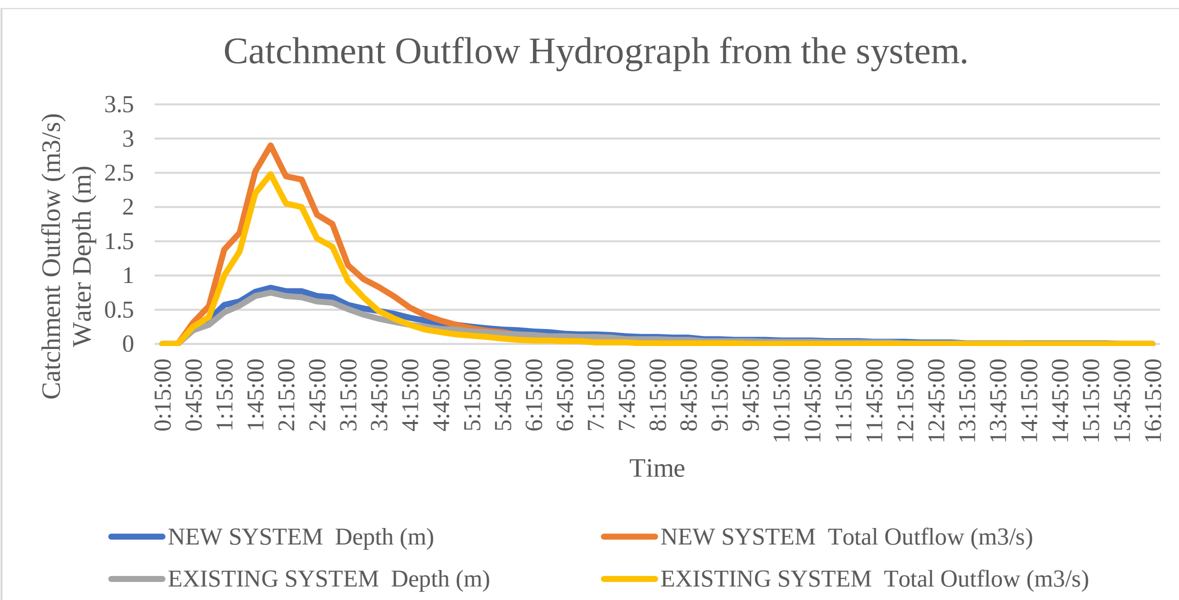

Figure 18: Catchment outflow hydrograph comparison of Existing and New System.

Figure 19 shows the water elevation profile in the drains and pipe along the path indicated by arrows in Fig 17 as it passes through the modelled temporary storage unit and until it reaches the outfall (O3)

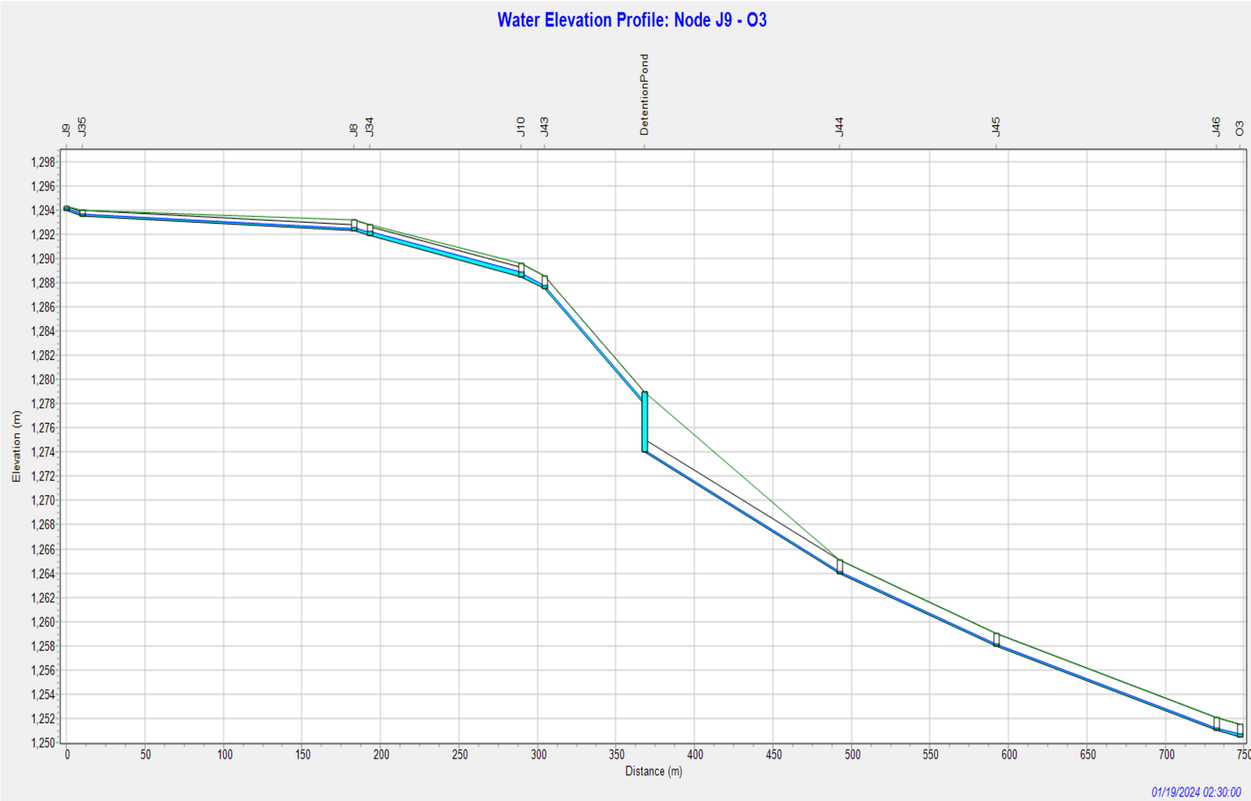

Figure 19: *Water Elevation profile along path (node J9 to O3).*

Implementation Process and Techniques

The designed system comprises of a network of trapezoidal drains of varying sizes, a detention pond to collect the runoff generated and facilitate a controlled discharge of the storm water into the environment down the slope to stable land through a slope drain. Implementation would however, involve the Gokwe Town Council, Ministry of Transport and the Ministry of Public Works within Gokwe for coherent works in solving the town's gully problems.

Conclusion

Gully erosion is a significant problem in urbanizing watersheds like Gokwe, Zimbabwe. The study investigated the factors influencing gully development, with a focus on stormwater management systems. This study demonstrates that redesigning stormwater management systems can effectively mitigate gully erosion in urbanizing areas like Gokwe, Zimbabwe. The proposed trapezoidal channel system, with its increased stormwater runoff collection efficiency and discharge capacity, reduces the rate of infiltration and therefore minimising the risks of challenges posed by loose, sandy soils and surpasses the existing system's limitations. By considering topographical and hydrological factors, the design ensures proper conveyance of peak runoff, promoting drainage infrastructure resilience and protecting surrounding areas from erosion. It is anticipated that the updated stormwater management system in Gokwe will reduce gully erosion and improve the durability of the drainage infrastructure. The efficient collection, transportation, and release of peak runoff to natural outlets is guaranteed by this design. The new trapezoidal open channel's design specifications were determined by calculation, yielding a width of 0.45 meters, a depth of 0.75 meters, 20% freeboard, and a 3:1 side slope.

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