FLOOD HYDROLOGICAL ASSESSMENT FOR THE PROPOSED MARULA PLATINUM SOLAR PV, LIMPOPO PROVINCE

Version 1

May 2023

HIGHLANDS HYDROLOGY (PTY) LTD

email: *luke@wiles.co.za* | **phone**: +27 72 129 4202

FLOOD HYDROLOGICAL ASSESSMENT FOR THE PROPOSED MARULA PLATINUM SOLAR PV, LIMPOPO PROVINCE

Prepared For

Scientific Aquatic Services (Pty) Ltd

Scientific Aquatic Services (Pty) Ltd
Reg No 2022/495100/07
Vat Reg. No. 4020235273
PO Box 751779
Gardenview
2047
Tel: 011 616 7893
Fax: 086 724 3132
E-mail: admin@sasenvironmental.co.za

Prepared By

Highlands Hydrology (Pty) Ltd

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1 INTRODUCTION

1.1 BACKGROUND

Highlands Hydrology (Pty) Ltd was appointed by Scientific Aquatic Services (Pty) Ltd to undertake a flood hydrological assessment for the proposed Marula Platinum Solar PV (hereafter referred to as 'the site') located near Driekop in the Limpopo Province of South Africa. The aim of the assessment was to determine flood-lines for the 1:50 and 1:100 year Recurrence Interval (RI), along the two non-perennial streams adjacent the site. The results of the modelling are aimed to inform any flood risk associated with the proposed solar development.

1.2 SCOPE OF WORK

The scope of work for the hydrological assessment included the following deliverables:

- *Site Examination* – the site was visited by Luke Wiles (a registered hydrologist), on the 15th March 2023. This was to enable a better understanding of the dominant hydrological flow regimes as well as confirm model inputs;
- *Baseline Assessment* – baseline climatic and hydrological data were sourced for the site. This included the interrogation of rainfall data, site specific design rainfall (depth/duration/frequency), evaporation, soils, natural vegetation, land-cover, as well as a regional and local hydrology;
- *Flood Assessment* – this involved the development of a suitable hydrological/hydraulic model of the river systems to determine the 1:50 and 1:100 year RI flood-lines, and
- A technical report detailing the achieved scope of work.

1.3 REGIONAL SETTING AND LAYOUT

The proposed site is located at approximately 24° 30' 38" S and 30° 4' 30" E. Figure 1-1 illustrates the regional setting of the proposed site, while Figure 1-2 presents the layout of proposed infrastructure at the site.

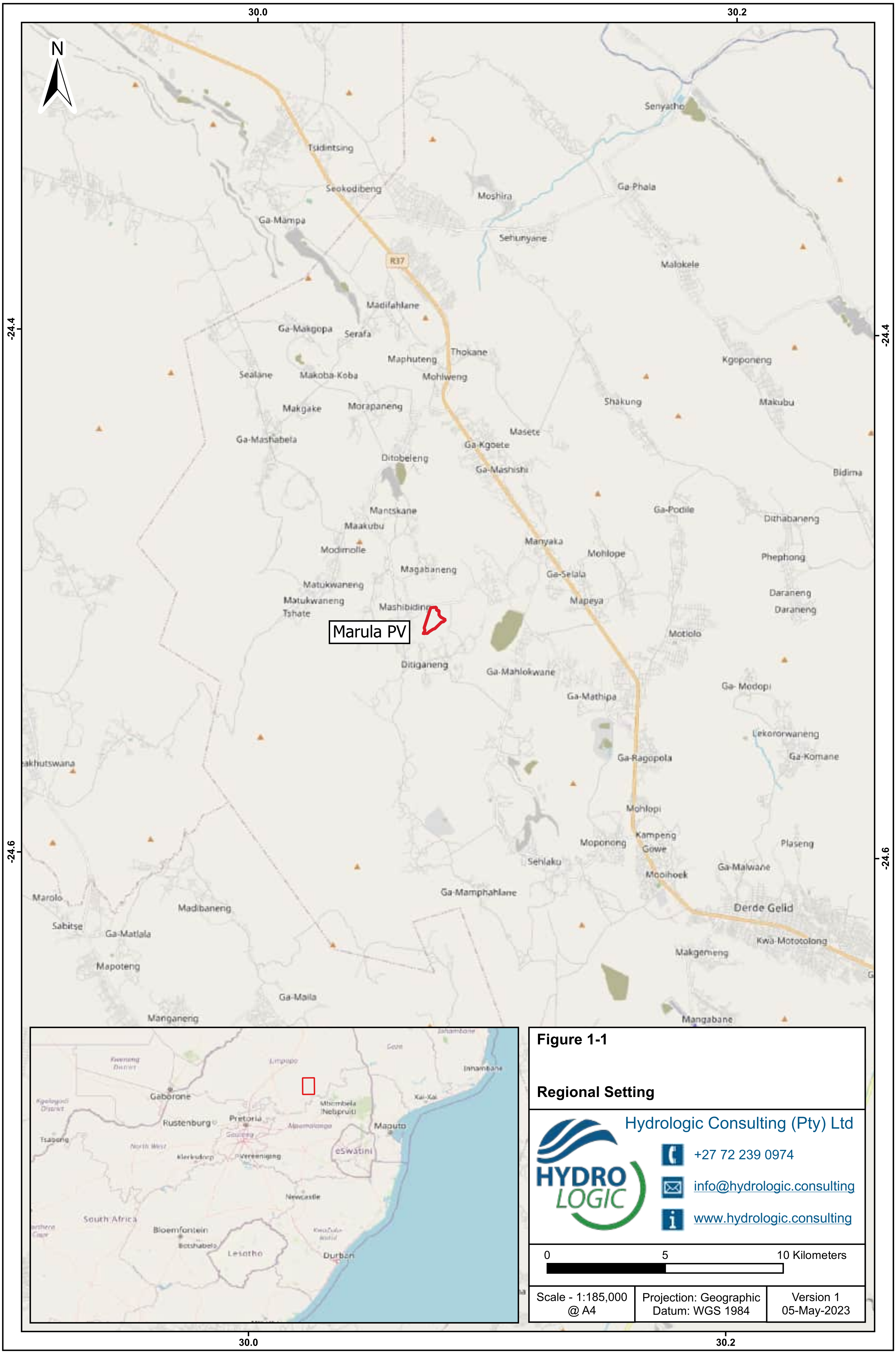
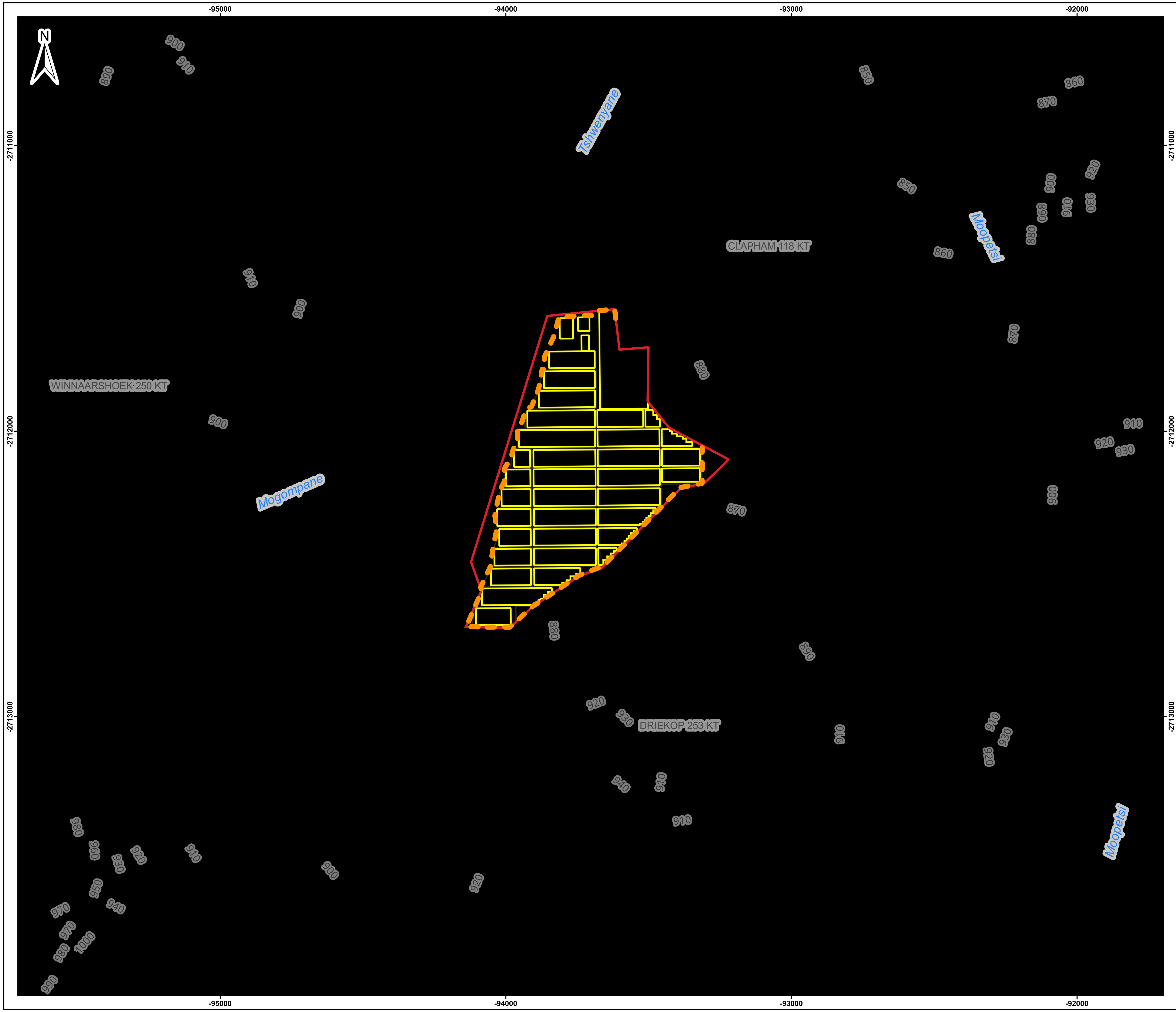


Figure 1-1

Regional Setting



Legend

- Boundary
- PV Block
- Access Road
- 5m Contour (50K Topo)
- Parent Farm
- Farm Portion
- Footpath (50K Topo)
- Other Road (50K Topo)
- Secondary Road (50K Topo)
- Street (50K Topo)
- River (Survey)
- 100m River Buffer (Survey Based
- Flood Protection Berm
- Drainage Canal (50K Topo)
- Non-Perennial River (50K Topo)
- Perennial River (50K Topo)
- Dam (50K Topo)
- Open Reservoir (50K Topo)

Figure 1-2

Layout

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0 250 500 m

Scale - 1:12,000 @ A3	Projection: Transverse Mercator Datum: Hartebeesthoek, LO31	Version 1 11-May-2023

2 BASELINE INFORMATION

Baseline information in this section includes rainfall, evaporation, design event rainfall, soils, vegetation and land-cover, as well regional and local topography hydrology.

2.1 RAINFALL

Various weather stations managed by both the South African Weather Services (SAWS) and the Department of Water and Sanitation (DWS) are positioned about the site as illustrated in Figure 2-1. The closest SAWS station to the site is SAWS station 636119 W (Forest Hill) located approximately 6km north-east of the site and has an altitude of 850m above mean sea level (site approximately 890m). This SAWS station has a record length of approximately 29 years with a Mean Annual Precipitation (MAP) of 478mm. There are no DWS rainfall stations in close proximity to the site.

The potential for rainfall distributions to change over distance can be significant. Figure 2-1 presents the variation in mean annual precipitation (MAP) in the greater area. As such, an alternative and site-specific source of rainfall data was used to provide average monthly rainfall values for the actual site as per Pegram *et al* (2016). This eliminates any risk associated with relying on a single rainfall station which may or may not be representative of the site.

Pegram *et al* (2016) includes details on the development of a raster database of monthly rainfall data for Southern Africa. Table 2-1 presents the site specific average monthly rainfall estimates from Pegram *et al* (2016) indicating a MAP of 551mm, comparing well to the distribution of rainfall as illustrated in Figure 2-1, as well as SAWS station 636119 W (478mm).Table 2-1 presents the average monthly rainfall estimates from Pegram *et al* (2016) for the site.

TABLE 2-1: AVERAGE MONTHLY RAINFALL DISTRIBUTION (MM)

Month	Rainfall (Pegram)
Jan	96
Feb	81
Mar	64
Apr	34
May	14
Jun	7
Jul	7
Aug	8
Sep	17
Oct	46
Nov	86
Dec	91
Total	**551**

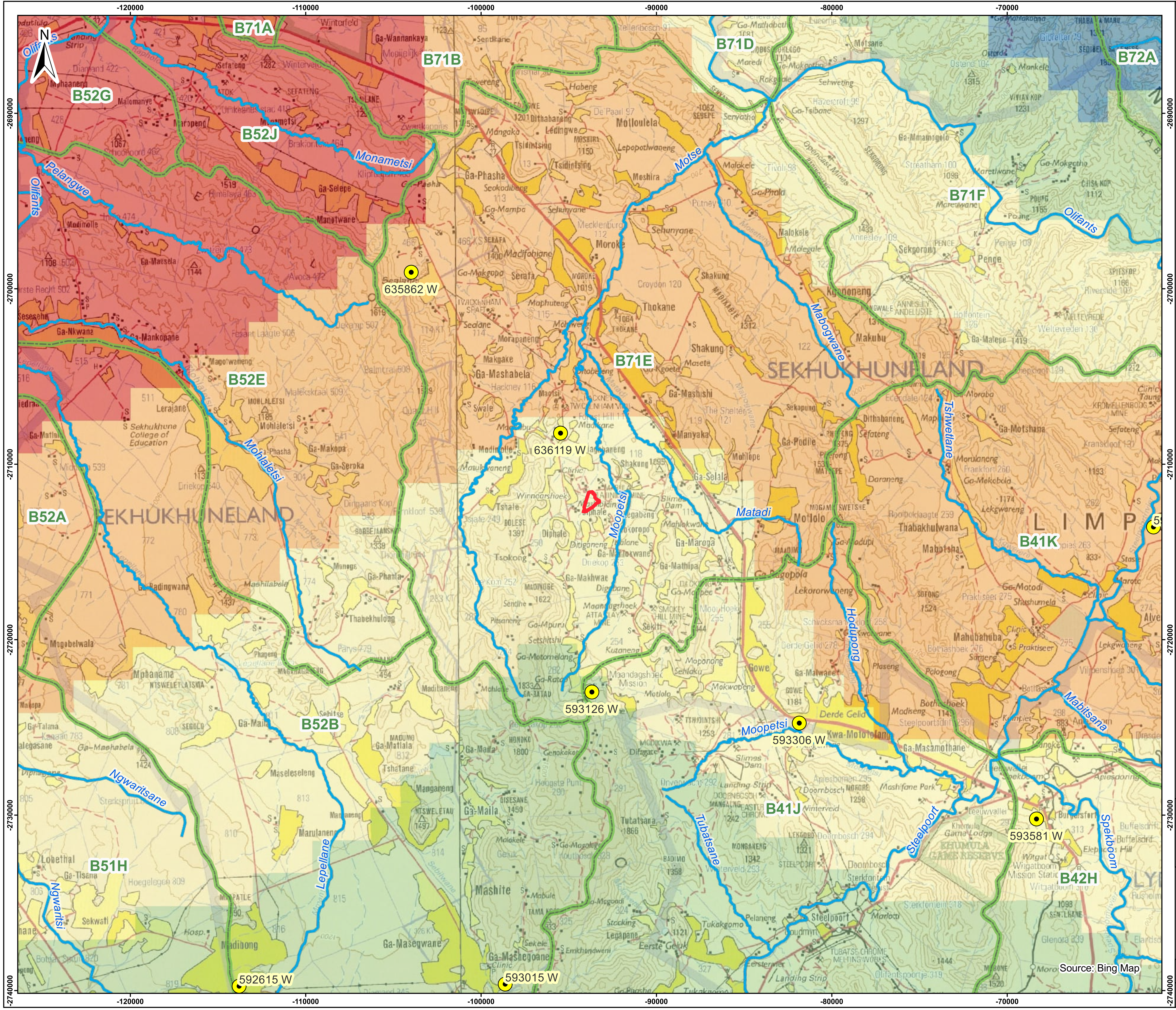


Figure 2-1

Weather Stations and Mean Annual Precipitation

2.2 1-DAY DESIGN RAINFALL DEPTHS

Design rainfall estimates for various recurrence intervals and durations were sourced from the Design Rainfall Estimation Software for South Africa (DRESSA), developed by the University of Natal in 2002 as part of WRC project K5/1060 (WRC, 2002). This method uses a regional l-moment algorithm in conjunction with a scale invariance approach to provide site-specific estimates of design rainfall (depth, duration and frequency), based on surrounding station records. WRC (2002) provides more detail on this method of design rainfall estimation. Table 2-2 presents the average DRESSA design rainfall estimates for the site.

TABLE 2-2: DRESSA 24-HOUR RAINFALL DEPTH

Recurrence Interval (Years)	Rainfall Depth (24 hour) (mm)
2	65
5	89
10	107
20	125
50	149
100	169
200	190

It is important to note, that no allowances for climate change were included in this study. A risk analysis using the expected life of a structure or process will indicate the relevance of considering climate change (i.e. as the expected life increases the influence of climate change increases). Climate change is expected to exacerbate any flooding due to an increase in rainfall intensities.

2.3 EVAPORATION

Evaporation data was sourced from the South African Atlas of Climatology and Agrohydrology (Schulze and Lynch, 2006) in the form of A-Pan equivalent potential evaporation. The average monthly evaporation distribution is presented in Table 2-3 and shows an annual potential evaporation of 2035mm.

TABLE 2-3: MONTHLY A-PAN EQUIVALENT POTENTIAL EVAPORATION

Month	Schulze & Lynch (2006)
Jan	216
Feb	177
Mar	177
Apr	142
May	128
Jun	107
Jul	118
Aug	153
Sep	184
Oct	208
Nov	212
Dec	213
Total	**2035**

2.4 AVERAGE CLIMATE

The average climate for the site is presented in Figure 2-2. While evaporation is showing as greatly exceeding rainfall, this is representative of the maximum A-Pan equivalent potential evapotranspiration that could occur assuming no limitations are placed on evaporative demand. The combination of rainfall, evaporation and temperature result in a hot arid steppe climate according to the Köppen-Geiger climate classification[1].

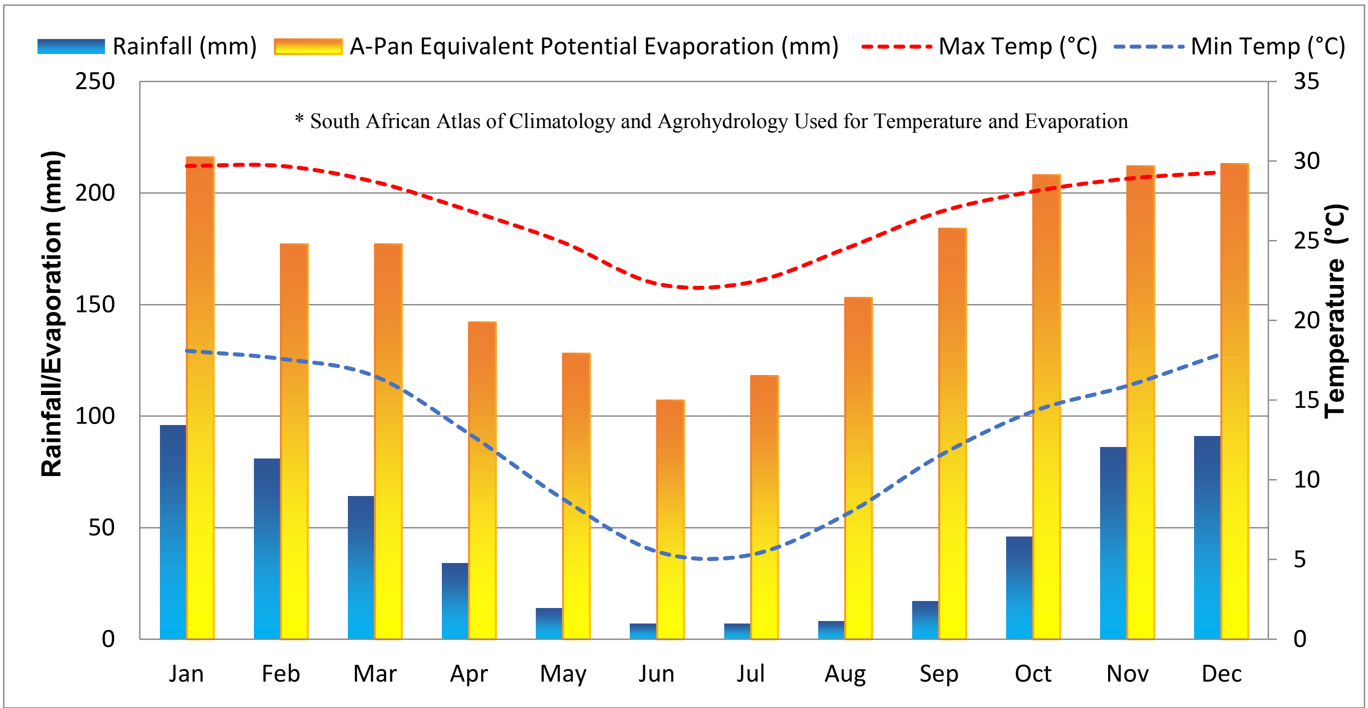


FIGURE 2-2: AVERAGE MONTHLY CLIMATE FOR THE SITE

2.5 TERRAIN

The following terrain (elevation) datasets were used in this study:

- 0.5m digital elevation model (DEM) interpolated from a 0.5m point cloud dataset provided for the site;
- 25m digital surface model (DSM) sourced from the National Geospatial Institutes (NGI) data; and
- NGI 10m contours.

This 0.5m DEM presents the result of a drone survey. This drone survey has been processed and provided as a 0.5m point cloud (point spacing of 0.5m). No metadata accompanied the 0.5m point cloud, which has been labelled as a DEM per its filename. A digital elevation model (DEM) is a non-specific term which applies to both a digital surface model (DSM) and a digital terrain model (DTM). As such, it is not possible to conclusively say whether the DEM contains surface features such as vegetation (in which case it would be a DSM), or if these surface features have been removed (thereby becoming a DTM representative of the 'bare earth').

What is apparent from the interpolated 0.5m DEM data, however, is that where vegetation is thick, terrain detail becomes poor. This is the limitation of a drone survey which uses photogrammetry and is only able to calculate elevation from surface features (as per the aerial imagery upon which the drone survey is based), with the result of

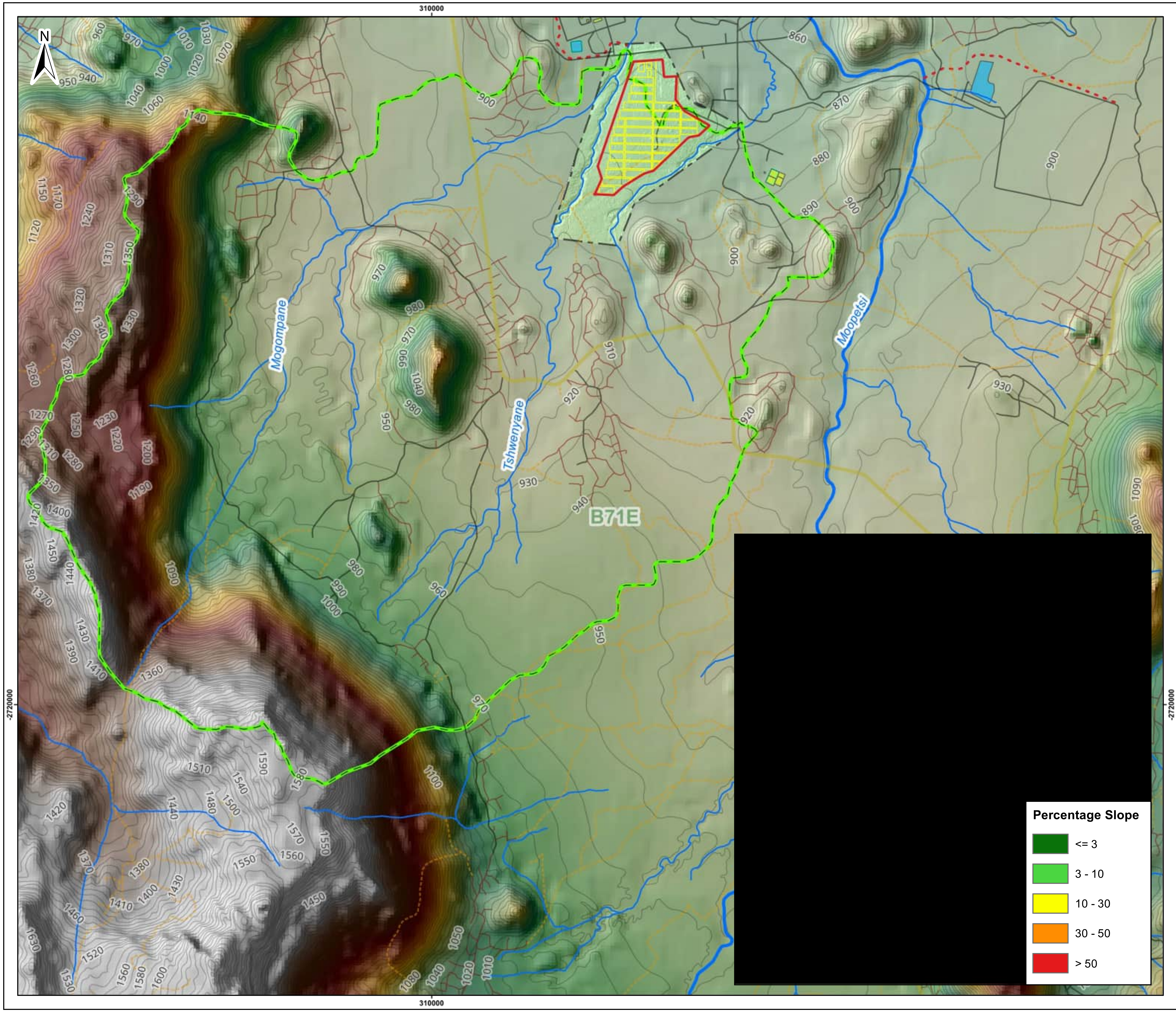
[1] http://stepsa.org/climate_koppen_geiger.html

a drone survey typically being a DSM. This suggests that the 0.5m DEM is a DSM and therefore does not present bare earth terrain. Figure 2-3 illustrates this limitation in the terrain data captured by the drone survey – specifically the slope map insert whereby a clear river channel is present in the western river while the eastern river exhibits a section with no river definition. A review of aerial imagery suggests this river channel is present, however, dense vegetation has obscured it from view (and from the drone survey). This presents one of the main limitations of this study – the accuracy of the drone survey in representing the terrain of the site. The extent of the drone survey is also of relevance with the eastern river in particular, positioned near the edge of the 0.5m DEM.

A secondary dataset using the NGIs 25m DSM enabled a high-level understanding of the terrain for the area not covered by the drone survey. This coarse data (with a 25m cell size) is not well suited to flood modelling.

Lastly, the 10m contours assist in the interpretation of the terrain illustrated in Figure 2-3. Elevations on-site approximate 890m AMSL.

Slopes on site are mild, below 3% in many locations and typically under 10% except for sections of river channels where channel banks are between 10% and 30%



Legend

- Boundary
- PV Block
- 5m Contour (50K Topo)
- 0.5m DEM Extent
- Footpath (50K Topo)
- Other Road (50K Topo)
- Secondary Road (50K Topo)
- Street (50K Topo)
- Flood Model Catchment Area (25m DSM Derived)
- Quaternary Catchment
- Drainage Canal (50K Topo)
- Non-Perennial River (50K Topo)
- Perennial River (50K Topo)
- Dam (50K Topo)
- Open Reservoir (50K Topo)

Elevation (mAMSL)

1,500

850

Figure 2-3

Terrain and Hydrology

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0 500 1,000 m

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2.6 HYDROLOGY

Figure 2-3 illustrates the hydrological setting of the site, while Figure 2-1 presents the river network of the greater region. The site is located within quaternary catchment B71E and drains into two non-perennial rivers located on the eastern (unnamed River) and western (Tshwenyane River) sides of the proposed PV development infrastructure. These non-perennial river systems drain in a northerly direction joining the perennial Moopetsie River downstream, which flows into the Motse River and ultimately, the Olifants River as illustrated in Figure 2-1. The mild slopes on site are not conducive to effective drainage and will more than likely result in ponding following significant rainfall events. A flood model catchment derived from the 25m DSM has been illustrated in Figure 2-3 and outlines the area of relevance to this study.

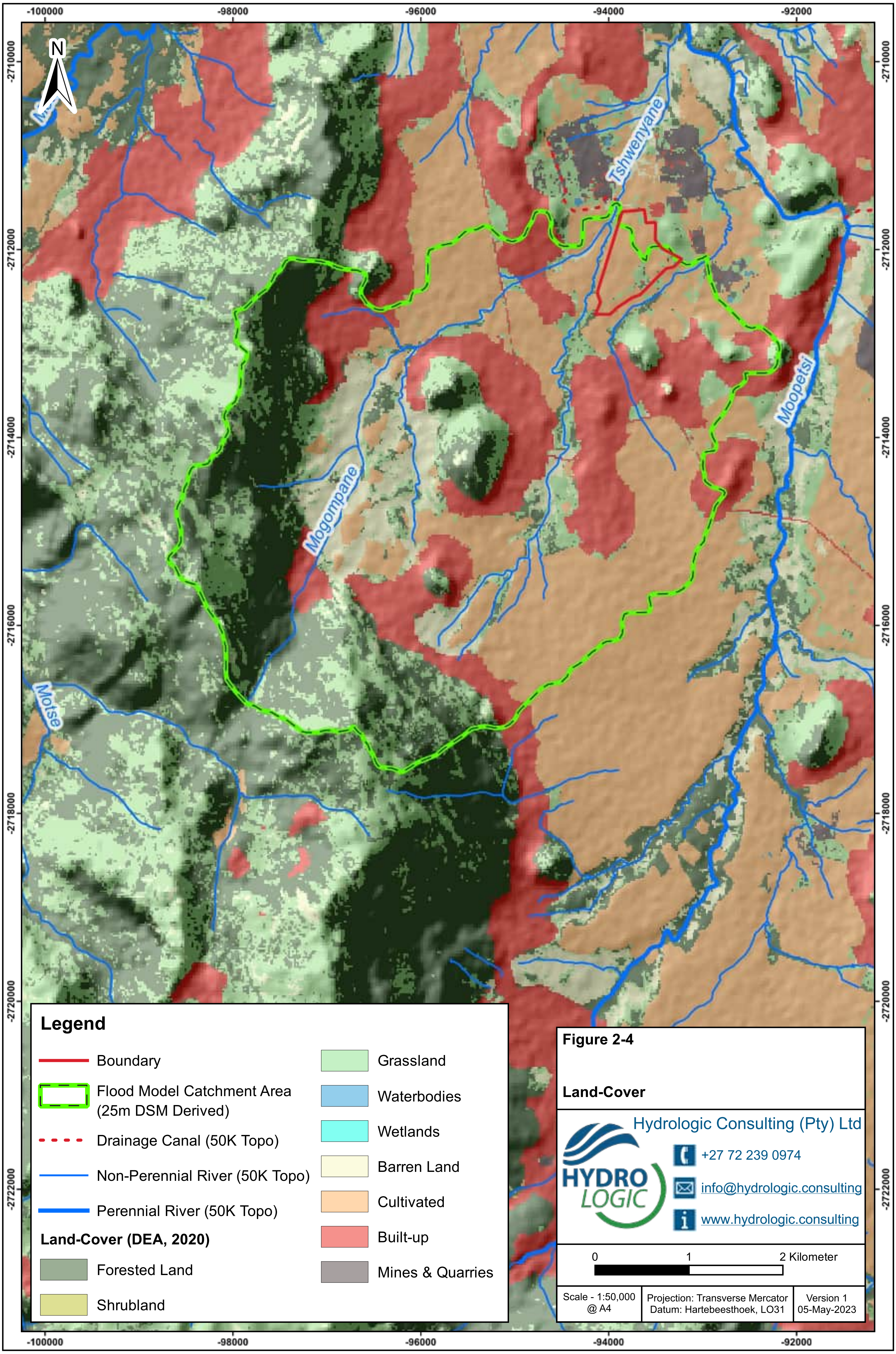
2.7 SOILS, VEGETATION AND LAND COVER

According to the Soil Conservation Service for South Africa (SCS-SA) dataset of the flood model of relevance, soils are classified as being predominantly in hydrological soil group B/C (moderately low to moderately high runoff potential) and group C (moderately high runoff potential). Group B/C soils cover the majority of the flood model catchment.

The natural vegetation of the site is classified as either Sekhukhune Mountain Bushveld or Sekhukhune Plains Bushveld according to SANBI (2018).

Per the Department of Environmental Affairs (DEA) 2020 dataset, land-cover over the flood model catchment is a mix of natural (grassland and forested land) and modified (built-up and cultivated).

Figure 2-4 illustrates the land cover distribution whilst Figure 2-5 illustrates the vegetation distribution and soil runoff potential at the site.



N
-100000
-98000
-96000
-94000
-92000
-2710000
-2712000
-2714000
-2716000
-2718000
-2720000
-2722000
Tshwenyane
Mogompane
Moopetsi
Motse
Legend
Boundary
Flood Model Catchment Area (25m DSM Derived)
Drainage Canal (50K Topo)
Non-Perennial River (50K Topo)
Perennial River (50K Topo)
Land-Cover (DEA, 2020)
Forested Land
Shrubland
Grassland
Waterbodies
Wetlands
Barren Land
Cultivated
Built-up
Mines & Quarries
Figure 2-4
Land-Cover
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0
1
2 Kilometer
Scale - 1:50,000 @ A4
Projection: Transverse Mercator
Datum: Hartebeesthoek, LO31
Version 1
05-May-2023

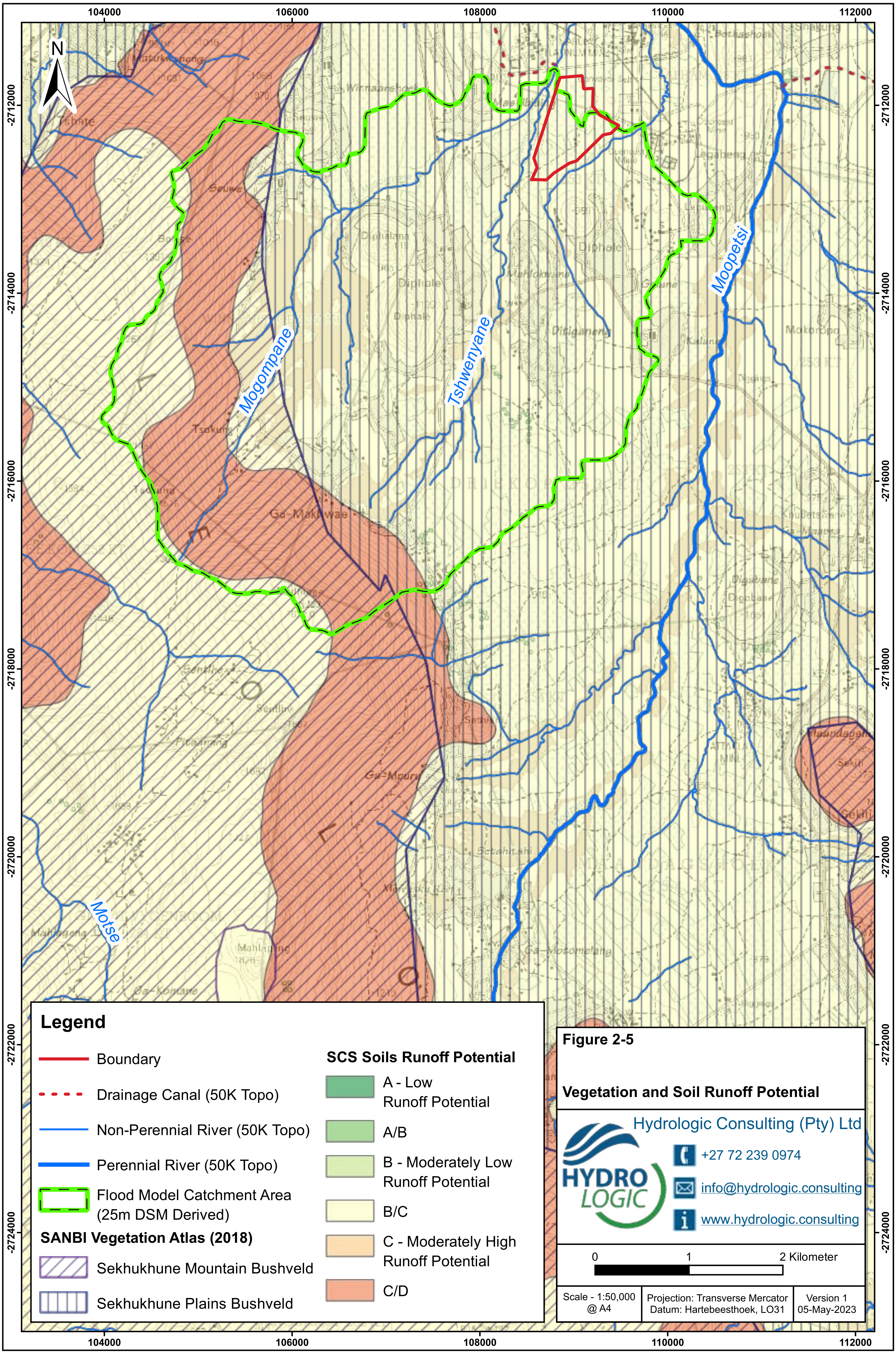


Figure 2-5

Vegetation and Soil Runoff Potential

3 FLOODING ASSESSMENT

A flood modelling exercise has been undertaken to determine flood-lines, flood depths and flood velocities for the 1:50 and 1:100 year RI for both the non-perennial streams located on the eastern and western side of the proposed PV infrastructure. The detail of the flood modelling for the site is presented in Appendix A. Since the modelling of flooding is (as undertaken), an approximation of reality, various assumptions and limitations are relevant (when considering the model results). These have been highlighted at various places in this report and are also outlined in Appendix A.

3.1 HYDRAULIC MODEL CHOICE

HEC-RAS 6.3.1 was selected to model flood hydrology and hydraulics using a 2D model approach. HEC-RAS is designed to perform one-dimensional and two-dimensional calculations for a full network of natural and constructed channels. The software is used worldwide and has been thoroughly tested (USACE, 2016, 2018).

3.2 FLOOD APPROACH

The defined 1:50,000 topographical map rivers to the east and west of the site were selected for modelling.

Flood modelling utilised the 0.5m DEM for the majority of the site, however, fringe areas required this 0.5m DEM data to be supplemented with the 25m DSM data. The 25m data is a coarse dataset not well suited to modelling flooding. Vertical alignment differences between the 0.5m DEM and 25m DSM required a vertical shift of +13.82m for the 25m DSM to match the 0.5m DSM (as determined by the average difference of a randomised sample of 1000 points). 13.82m is a large difference and was compared against the 10m contour data. This comparison suggests that the 0.5m DEM is approximately 13m out from the contour data (and 25m DSM data) – essentially indicating that the vertical datum of the 0.5m DEM data does not match the vertical datum typically used in South Africa. Nevertheless, since the 0.5m DEM data is the core data for the flood model, its vertical datum was left unaltered. Flood model results are consequently based upon the 0.5m DEM vertical datum.

The 0.5m DEM and 25m DEM (+13.82m) were subsequently used in the development of a hydrological (PCSWMM) model and a hydraulic (HEC-RAS) model.

The PCSWMM model utilised 52 subcatchments connected by hypothetical trapezoidal channels in most locations, except for where 0.5m DEM data enabled transects of the channels to be extracted (for 5 out of 40 channel sections modelled). Each subcatchment had its hydrological parameters informed by site-specific datasets. The output of PCSWMM was three 1:50 and 1:100 RI, 24-hour design hydrographs that were applied to the two non-perennial rivers east and west of the site.

The availability of a continuous 1m DTM allowed for the adoption of a 2D flood model approach using HEC-RAS. Unlike a 1D approach (using cross-sections) which samples the DTM at set cross-section locations, a 2D model approach uses a continuous model grid. The advantage of a 2D model is consequently its ability to account for more variation in the topographic data since no gaps are present in the model geometry (as is the case with cross-sections). The western river (the Tshwenyane River) is reasonably well defined in the 0.5 DEM. The eastern river (an unnamed non-perennial) is, however, poorly defined due to the dense vegetation coverage that the drone survey cannot 'see through'. This has implications concerning the flood modelling – both its accuracy and the extent of flooding as noted in the following section. The extent of the flood model covered approximately 3km of the defined river.

A single road crossing on the Tshwenyane River was added to the HEC-RAS model. This road crossing required some edits to the 0.5m DEM to approximate the road crest which was absent or otherwise too high (in error) as well as the river channel (which was likewise absent). Neither of the aforementioned should be present in the 0.5m DEM data with both considered 0.5m DEM errors. Manual edits while improvements on the 0.5m DEM, are nevertheless estimates which will introduce error.

A second road crossing on the eastern river could not be added as the extent of the 0.5m DEM was insufficient for this purpose. This road crossing is approximately 250m downstream of the downstream boundary of the eastern river. The absence of this crossing will potentially influence flood results by reducing flooding towards the road (given the absence of the bottlenecking influence of the crossing). However, as noted in the following section, large inaccuracies in the 0.5m DEM are already present while the 250m distance will reduce the potential influence of excluded crossing.

3.3 FLOOD MODELLING RESULTS

The overall results of the flood modelling are presented in Figure 3-1, which illustrates the 1:50 and 1:100 year RI flood-lines. A 100m watercourse buffer (defined according to the NGI's 1:50,000 topographical map dataset) is also presented in Figure 3-1. Figure 3-2 illustrates the maximum depth associated with the 1:100 RI flood event while Figure 3-3 illustrates the maximum flood velocity associated with the 1:100 RI flood event.

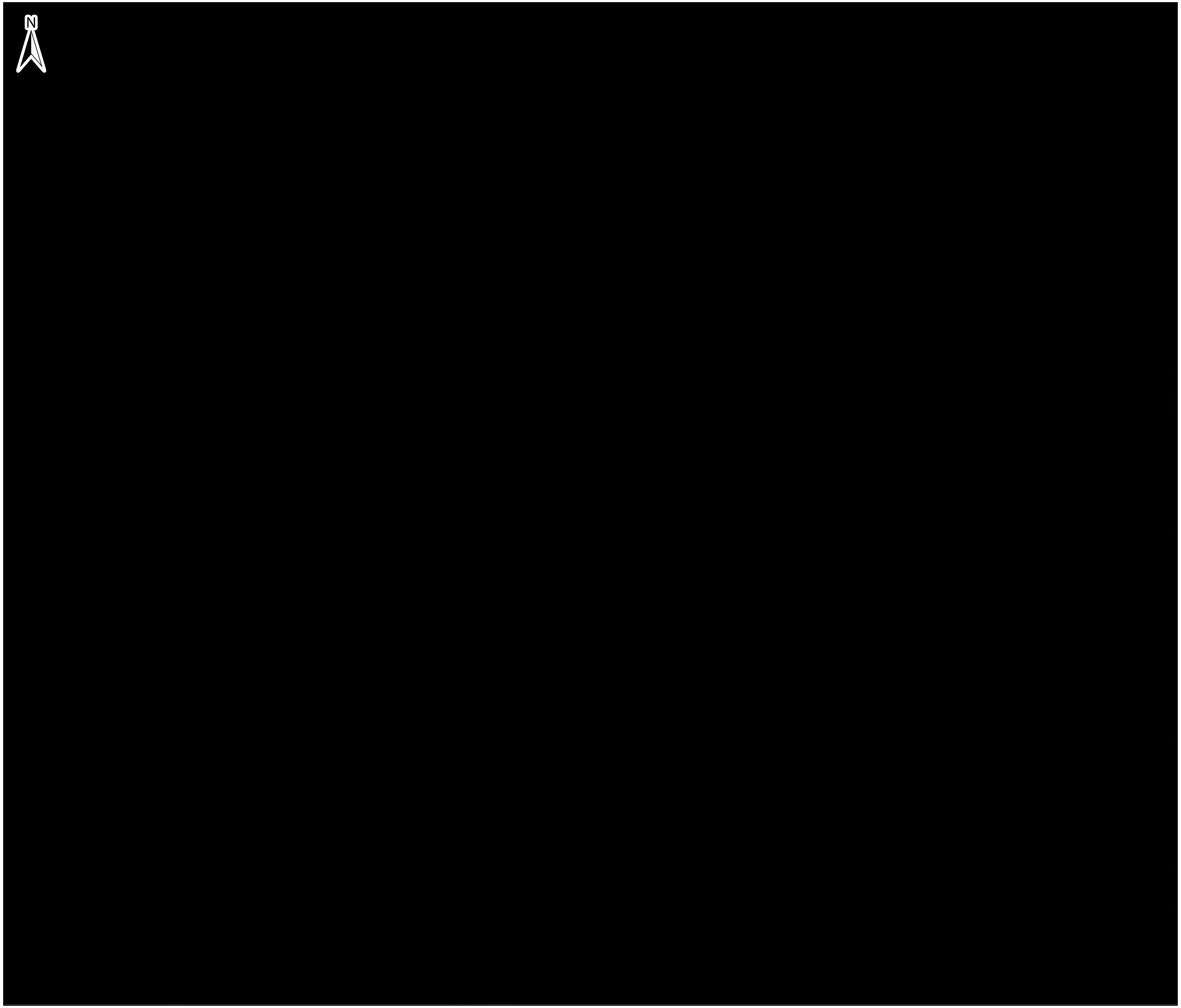
Model results reveal significantly higher containment of flooding in the western river channel versus the eastern river channel. This is largely due to the poor definition of the river channel in the eastern river (per the 0.5m DEM data). Figure 3-1 clarifies this with no channel definition visible in the middle reach of the eastern river (resulting from dense vegetation that the drone survey cannot penetrate).

This inability of the drone survey to penetrate dense vegetation alludes to another possible limitation of the flood model, which is that the 0.5m DEM may contain surface features (i.e. vegetation). If this is the case, then the vegetation may create an artificially high surface. This has the potential to form a deeper river channel than actual if the channel is bordered by an artificially high surface (due to the 0.5m capturing vegetation). It is unknown if this is the case. The 0.5m point cloud will need to have its metadata provided to confirm whether this is occurring (i.e. what processing of the drone imagery has been performed).

At the road crossing, the six 3m x 2.4m culverts can convey a large portion of the flood (approximately 70m^3/s of the near 270m^3/s 1:100 year RI flood peak). Excess flows above 70m^3/s are routed over the top of the road and into the downstream environment. This bottleneck at the road crossing causes a backup of water with some of this water being routed to the east and out of the 2D flood model boundary. The performance of the six culverts is likely influence by the 0.5m DEM data which indicates that the river channel rises (upstream to downstream). This is likely an error in the 0.5m DEM data.

Some 'glass walling' of the modelled flooding is present to the east of the site where the interface between the 0.5m DEM and 25m DSM is poor. This causes a hypothetical wall to be present in the model that limits the movement of flooding. This likely exacerbates flooding on the site (to the east) as water cannot spread due to the 'glass wall' and instead pushes towards the site more. On the west, the interface with the 25m DSM does not cause glass walling, however, the reader is cautioned concerning the accuracy of the resulting flooding since the 25m data is coarse and will only represent terrain at a high level. Some (error in the western river is consequently expected due to the reliance on a section of 25m DSM data.

Figure 3-3 (velocity) reveals the increased flow velocity in the western channel where a defined river channel enables the concentration of flow. This concentration of flow is absent from the eastern channel where a poorly defined channel is present.



Legend

- Boundary
- PV Block
- 5m Contour (50K Topo)
- 0.5m DEM Extent
- Footpath (50K Topo)
- Other Road (50K Topo)
- Street (50K Topo)
- Drainage Canal (50K Topo)
- Non-Perennial River (50K Topo)
- Dam (50K Topo)
- Flood-Line (1:100 RI Event)
- Flood-Line (1:50 RI Event)
- Bridge / Raised Road
- Culverts (Six 3m x 2.4m)
- 2D Flood Model Boundary
- 100m River Buffer (Survey Derive

Elevation (mAMSL)

910

880

Figure 3-1

Flood-Lines

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0 100 200 m

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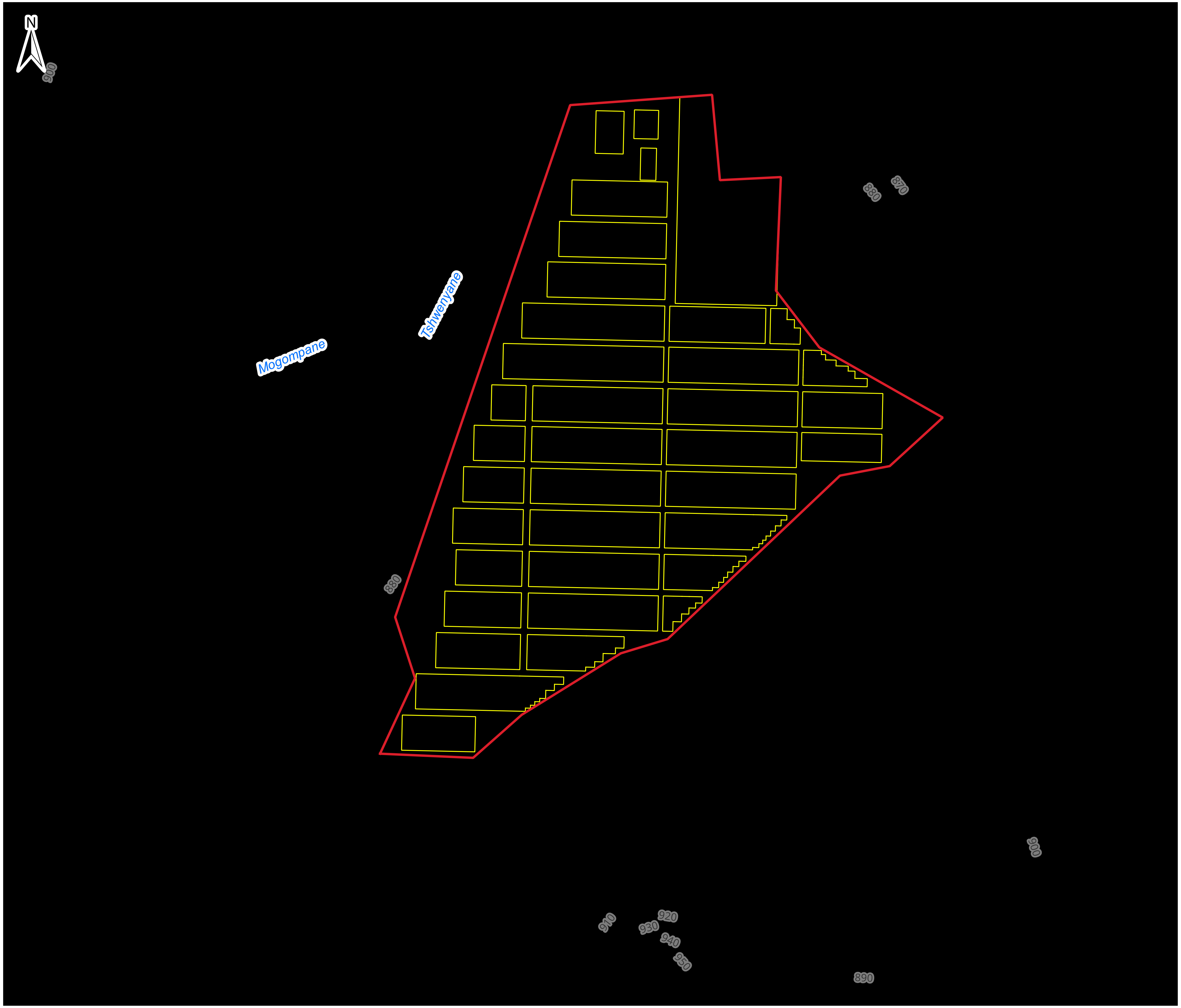

Legend

- Boundary
- PV Block
- 5m Contour (50K Topo)
- 0.5m DEM Extent
- Footpath (50K Topo)
- Other Road (50K Topo)
- Street (50K Topo)
- Drainage Canal (50K Topo)
- Non-Perennial River (50K Topo)
- Dam (50K Topo)
- Culverts (Six 3m x 2.4m)
- 2D Flood Model Boundary
- 100m River Buffer (Suvey Based)

Max. Depth (1:100 RI)

- <= 0.2
- 0.2 - 0.5
- 0.5 - 1.0
- > 1.0

Figure 3-2

Maximum Flood Depth (1:100 RI)

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0 100 200 m

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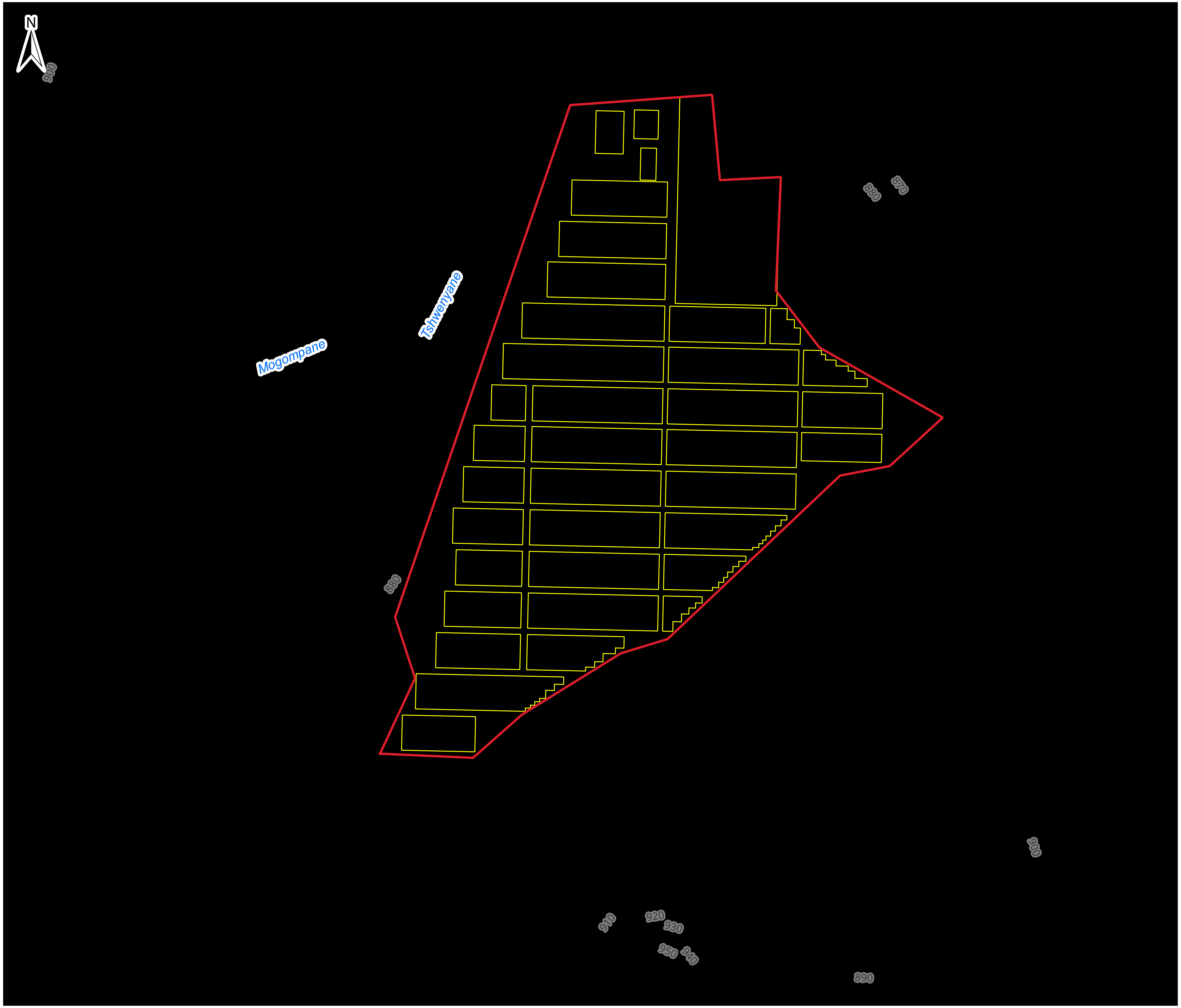

Legend

- Boundary
- PV Block
- 5m Contour (50K Topo)
- 0.5m DEM Extent
- Footpath (50K Topo)
- Other Road (50K Topo)
- Street (50K Topo)
- Drainage Canal (50K Topo)
- Non-Perennial River (50K Topo)
- Dam (50K Topo)
- Culverts (Six 3m x 2.4m)
- 2D Flood Model Boundary
- 100m River Buffer (Survey Based

Max. Velocity (m/s)

- <= 0.5
- 0.5 - 1.0
- 1.0 - 1.5
- 1.5 - 2.0
- > 2.0

Figure 3-3

Maximum Flood Depth (1:100 RI)

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0 100 200 m

Scale - 1:6,000 @ A3 | Projection: Transverse Mercator Datum: Hartebeesthoek, LO31 | Version 1 11-May-2023

3.4 FLOOD PROTECTION

Due to the low confidence in flood model results and potential flood risk to proposed infrastructure it is recommended that mitigation in the form of flood protection be considered at the site. Figure 1-2 illustrates an indicative position that flood protection berms could be placed to help manage flood risk to infrastructure should river levels rise. Figure 3-4 illustrates a typical flood protection berm which could be utilised to mitigate potential flood risk to proposed infrastructure from adjacent streams. These berms have not been sized in this report as the hydrological/hydraulic modelling associated with this falls outside of the scope of this report.

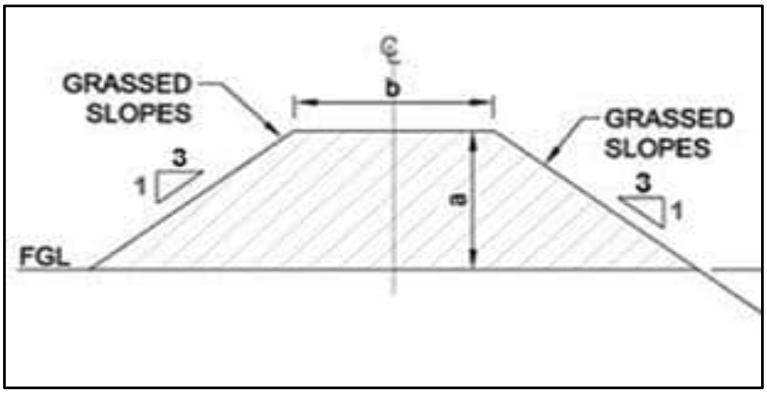

FIGURE 3-4: TYPICAL FLOOD PROTECTION BERM

4 CONCLUSIONS AND RECOMMENDATIONS

Baseline Assessment

Baseline information including monthly rainfall, monthly evaporation, design event rainfall, soils, vegetation and land cover, as well as site topography and regional and local catchment hydrology were considered for the proposed Marula Platinum Solar PV project, located near Driekop in the Limpopo Province of South Africa. This baseline confirmed that although the site is located within a fairly hot, arid steppe climatic zone, the design rainfall depths associated with extreme events are still significant at 149mm and 169mm for the 24-hour, 1:50 and 1:100 RI respectively.

Elevation data for the site was obtained in the form of the following datasets:

- 0.5m digital elevation model (DEM) interpolated from a 0.5m point cloud dataset provided for the site;
- 25m digital surface model (DSM) sourced from the National Geospatial Institutes (NGI) data; and
- NGI 10m contours.

The site is located within quaternary catchment B71E and drains into two non-perennial rivers located on the eastern (unnamed River) and western (Tshwenyane River) sides of the proposed PV development infrastructure. These non-perennial river systems drain in a northerly direction joining the perennial Moopetsie River downstream, which flows into the Motse River and ultimately, the Olifants River. The mild slopes on site are not conducive to effective drainage and will more than likely result in ponding following significant rainfall events. The combination of significant extreme event rainfall events contributing to large peak flows as well as the flat topography associated with the site, confirm a potential flood risk insofar as the ability of the river systems to effectively route storm water downstream during significant flood events.

Flood Assessment

A flood model was developed to determine flood-lines (1:50 and 1:100 year RI), flood depths (1:100 year RI) and flood velocities (1:100 year RI) for both the non-perennial streams located on the eastern and western side of the proposed PV infrastructure. Critical to the confidence in the model outputs, is the quality of the elevation survey used in the modelling. The supplied 0.5m DEM presents the result of a drone survey. This drone survey was processed and provided as a 0.5m point cloud (point spacing of 0.5m). No metadata accompanied the data and as such it is not possible to conclusively say whether the DEM contains surface features such as vegetation (in which case it would be a DSM), or if these surface features have been removed (thereby becoming a DTM representative of the 'bare earth'). What is apparent from the interpolated 0.5m DEM data, however, is that where vegetation is thick, terrain detail becomes poor. This is the limitation of a drone survey which uses photogrammetry and is only able to calculate elevation from surface features (as per the aerial imagery upon which the drone survey is based), with the result of a drone survey typically being a DSM. This suggests that the 0.5m DEM is a DSM and therefore does not present bare earth terrain. The extent of the drone survey is also limited, particularly at the eastern river which is located near the edge of the 0.5m DEM.

Flood modelling utilised the 0.5m DEM for the majority of the site, however, fringe areas required this 0.5m DEM data to be supplemented with the 25m DSM data. The 25m data is a coarse dataset not well suited to modelling flooding. Vertical alignment differences between the 0.5m DEM and 25m DSM required a vertical shift of +13.82m for the 25m DSM to match the 0.5m DSM (as determined by the average difference of a randomised sample of

1000 points). 13.82m is a large difference and was compared against the 10m contour data. This comparison suggests that the 0.5m DEM is approximately 13m out from the contour data (and 25m DSM data) – essentially indicating that the vertical datum of the 0.5m DEM data does not match the vertical datum typically used in South Africa. Nevertheless, since the 0.5m DEM data is the core data for the flood model, its vertical datum was left unaltered. Flood model results are consequently based upon the 0.5m DEM vertical datum.

The 0.5m DEM and 25m DEM (+13.82m) were subsequently used in the development of a hydrological (PCSWMM) model and a hydraulic (HEC-RAS) model. The PCSWMM model utilised 52 subcatchments connected by hypothetical trapezoidal channels in most locations, except for where 0.5m DEM data enabled transects of the channels to be extracted (for 5 out of 40 channel sections modelled). Each subcatchment had its hydrological parameters informed by site-specific datasets. The output of PCSWMM was three 1:50 and 1:100 RI, 24-hour design hydrographs that were applied to the two non-perennial rivers east and west of the site.

The availability of a continuous 1m DTM allowed for the adoption of a 2D flood model approach using HEC-RAS. Unlike a 1D approach (using cross-sections) which samples the DTM at set cross-section locations, a 2D model approach uses a continuous model grid. The advantage of a 2D model is consequently its ability to account for more variation in the topographic data since no gaps are present in the model geometry (as is the case with cross-sections). The western river (the Tshwenyane River) is reasonably well defined in the 0.5 DEM. The eastern river (an unnamed non-perennial) is, however, poorly defined due to the dense vegetation coverage that the drone survey cannot 'see through'. This has implications concerning the flood modelling – both its accuracy and the extent of flooding. The extent of the flood model covered approximately 3km of the defined river. A single road crossing with six identical culverts (3m x 2.4m) on the Tshwenyane River was added to the HEC-RAS model.

A second road crossing on the eastern river could not be added as the extent of the 0.5m DEM was insufficient for this purpose. This road crossing is approximately 250m downstream of the downstream boundary of the eastern river. The absence of this crossing will potentially influence flood results by reducing flooding towards the road (given the absence of the bottlenecking influence of the crossing).

Model results reveal significantly higher containment of flooding in the western river channel versus the eastern river channel. This is largely due to the poor definition of the river channel in the eastern river. An increased flow velocity in the western channel is evident where a defined river channel enables the concentration of flow. This concentration of flow is absent from the eastern channel where a poorly defined channel is present. At the road crossing, the six 3m x 2.4m culverts can convey a large portion of the flood (approximately 70m^3/s of the near 270m^3/s 1:100 year RI flood peak). Excess flows above 70m^3/s are routed over the top of the road and into the downstream environment. This bottleneck at the road crossing causes a backup of water with some of this water being routed to the east and out of the 2D flood model boundary.

Some 'glass walling' of the modelled flooding is present to the east of the site where the interface between the 0.5m DEM and 25m DSM is poor. This causes a hypothetical wall to be present in the model that limits the movement of flooding. This likely exacerbates flooding on the site (to the east) as water cannot spread due to the 'glass wall' and instead pushes towards the site more. On the west, the interface with the 25m DSM does not cause glass walling, however, the reader is cautioned concerning the accuracy of the resulting flooding since the 25m data is coarse and will only represent terrain at a high level.

In considering the above, the quality of the input elevation data, together with the limitations in extent, affected the quality of flood model and associated confidence in results.

It is recommended that a revised flood model be developed using a LiDAR data survey, able to penetrate the dense vegetation and provide a bare-earth DTM better suited to flood modelling. It recommended that Lidar be flown at a low altitude to improve point density and thereby potential for vegetation canopy penetration. The LiDAR survey should also be extended to cover the eastern and western river channels and adjacent areas beyond the extent of the 0.5m DEM, plus the river channel up to the bridge on the eastern river.

By flying a Lidar survey, the accuracy of the flood modelling can be significantly improved and the result of this improved accuracy may reveal that the flood risk to the site is substantially diminished, through the containment of flooding in a defined river channel. It is also possible however that after remodelling using improved LiDAR, flooding may increase in places due to the lowering of the flood model surface to actual when compared to the artificially increased 0.5m DEM due to vegetation present in the data. Nonetheless, model accuracy and confidence in associated flood risk will be significantly higher. Due to the limitations in confidence in the flood modelling, a flood protection berm was indicatively placed to serve as mitigation from potential flooding of adjacent streams.

Luke Wiles (MSc, PrSciNat)

Project Manager/Author/Reviewer

Mark Bollaert (MSc, PrSciNat)

Project Author

5 REFERENCES

Bailey, A.K. and Pitman, W.V., 2015, "*Water Resources of South Africa 2012 Study (WR2012)"*, WRC Report No. TT, Water Research Commission, Pretoria

Chow, V.T., 1959, *"Open-Channel Hydraulics"*, McGraw-Hill, New York

Department of Water Affairs and Forestry, 1998. *National Water Act, Act 36 of 1998*

Department of Water Affairs and Forestry, 1999. *Government Notice 704 (Government Gazette 20118 of June 1999)*

Department of Water Affairs and Forestry, 2006, "*Best Practice Guideline No. G1: Storm Water Management*" , DWAF, Pretoria, August 2006

HRU – Hydrological Research Unit, 1978, *"A Depth-Duration-Frequency Diagram for Point Rainfall in southern Africa"*, Report 2/78, University of Witwatersrand, Johannesburg, South Africa

Lynch, S.D., 2004, "*Development of a Raster Database of Annual, Monthly and Daily Rainfall for Southern Africa*". WRC Report 1156/1/04. Water Research Commission, Pretoria, South Africa.

Pegram, G.G.S., Sinclair, S. and Bárdossy, A., 2016, "*New Methods of Infilling Southern African Rain gauge Records Enhanced by Annual, Monthly and Daily Precipitation Estimates Tagged with Uncertainty"*

Rossman, L., 2008. Storm Water Management Model user's manual, version 5.0, (March), 271. Retrieved from http://nepis.epa.gov/Exe/ZyPURL.cgi?Dockey=P10011XQ.txt

SANRAL., 2013 "*Drainage Manual - Sixth Edition*", The South African National Roads Agency Limited, Pretoria.

Schulze, R.E. and Lynch, S.E., 2006. "*South African Atlas of Climatology and Agrohydrology",* WRC Report 1489/1/06, Water Research Commission, Pretoria

Smithers, J.C. and Schulze, R.E., 2000, "*Long Duration Design Rainfall Estimates for South Africa*", WRC Report No. 811/1/00, Water Research Commission, Pretoria

Water Research Commission 2002. Design Rainfall Estimation in South Africa. WRC Report No. K5/1060

APPENDIX A: FLOOD MODELLING

A.1 HYDROLOGICAL MODEL

A hydrological model was required to first be developed for the contributing catchment routing through the current double culvert.

A.1.1 HYDROLOGICAL MODEL CHOICE

PCSWMM is a model package that makes use of the USEPA Storm Water Management Model (SWMM), which is a computer program that computes dynamic rainfall-runoff from developed urban and undeveloped or rural areas (Rossman, 2008).

The SWMM model suited application to this study since it could account for:

- Time-varying rainfall;
- Rainfall interception in depression storage;
- Infiltration of rainfall into unsaturated soil layers;
- Routing of overland flow;
- Dynamic wave flow routing of flood waters; and
- Capture and retention of rainfall/runoff.

The hydrological modelling as it pertains to the development of stormwater management plans and flooding assessments using SWMM has been undertaken for many thousands of studies throughout the world (Rossman, 2008), including South Africa and was well suited to deriving the upstream inflows and effective rainfall as input into the hydraulic component of this study.

A.1.2 HYDROLOGICAL MODEL DOMAIN

The 25m DSM formed the basis of the hydrological model domain, informing the partitioning of subcatchments, the accumulation of flow and some parameterisation of the model (e.g. subcatchment slope). Subcatchments of interest were derived through geoprocessing of the available elevation data. Sequential computations of flow direction, flow accumulation and stream definition based upon a contributing area of 50ha were then used to delineate subcatchments.

A.1.3 SUBCATCHMENT PARAMETERISATION

Land cover parameters were estimated according to the SCS-SA soil for the area of interest, DEA land-cover, the 25m DSM and satellite imagery, for each of the 52 subcatchments. These were used to populate model attributes relating to depression storage, surface roughness, infiltration loss, slope and impervious areas.

A.1.4 DESIGN RAINFALL

In assessing flooding, it was necessary to define the associated rainfall that would cause this flooding. A hypothetical storm consequently needed to be developed which utilised the depth-duration-frequency (DDF) data provided by DRESSA (see Section 2.2). This hypothetical storm is the design rainfall that will produce the highest degree of flooding at each location independent of catchment response time (which is the index of the rate at which stormflow moves through a catchment). To calculate the hypothetical storm, the DRESSA 1:50 and 1:100 year RI rainfall depths for various durations (e.g. 5 minutes, 30 minutes and 2 hours) were transformed into a synthetic rainfall distribution or design hyetograph. The DRESSA estimates used were those relevant to the flooding component of the study.

When considering the catchment area upstream, it was not necessary to include an areal reduction factor that considers the difference between the design rainfall estimate for a point versus that over a large catchment (since larger catchments are less likely to experience high-intensity storms over the full catchment area). An areal reduction factor of 97.3% was calculated, however, more conservative approach of 100% was adopted (where greater rainfall is conservative).

A.1.5 DESIGN HYDROGRAPHS

The 1:50 and 1:100 year RI design hydrographs were extracted from the PCSWMM model at three locations (for application on the two river reaches to be modelled). A comparison of the downstream modelled hydrographs estimated using PCSWMM to the Regional Maximum Flood (RMF) and Standard Design Flood (SDF) methods was made. These alternate flood estimation methods provide peak flow estimates that are generated using a regional approach and can sometimes be used as a high-level validation of modelled stormflows. Their influence on the PCSWMM model resulted in the PCSWMM model being revised to produce higher peaks (since both the RMF and SDF demonstrated higher peaks than PCSWMM).

Differences between the regional RMF and SDF methods and the site-specific PCSWMM estimates are expected, however, with Figure A-1 illustrating this difference. The PCSWMM model was adjusted to produce higher flows (than those produced from the original model).

It is, however, also the specific hydrological characteristics of the subcatchments upstream of the crossing, which lead to one of the largest uncertainties concerning the flood modelling undertaken. The parameterisation of these subcatchments has utilised site-specific datasets, however, some inaccuracy is expected with the potential for the peak flows and design hydrographs to vary in reality. Lack of calibration due to an absence of observed flows means that the PCSWMM model results couldn't be verified.

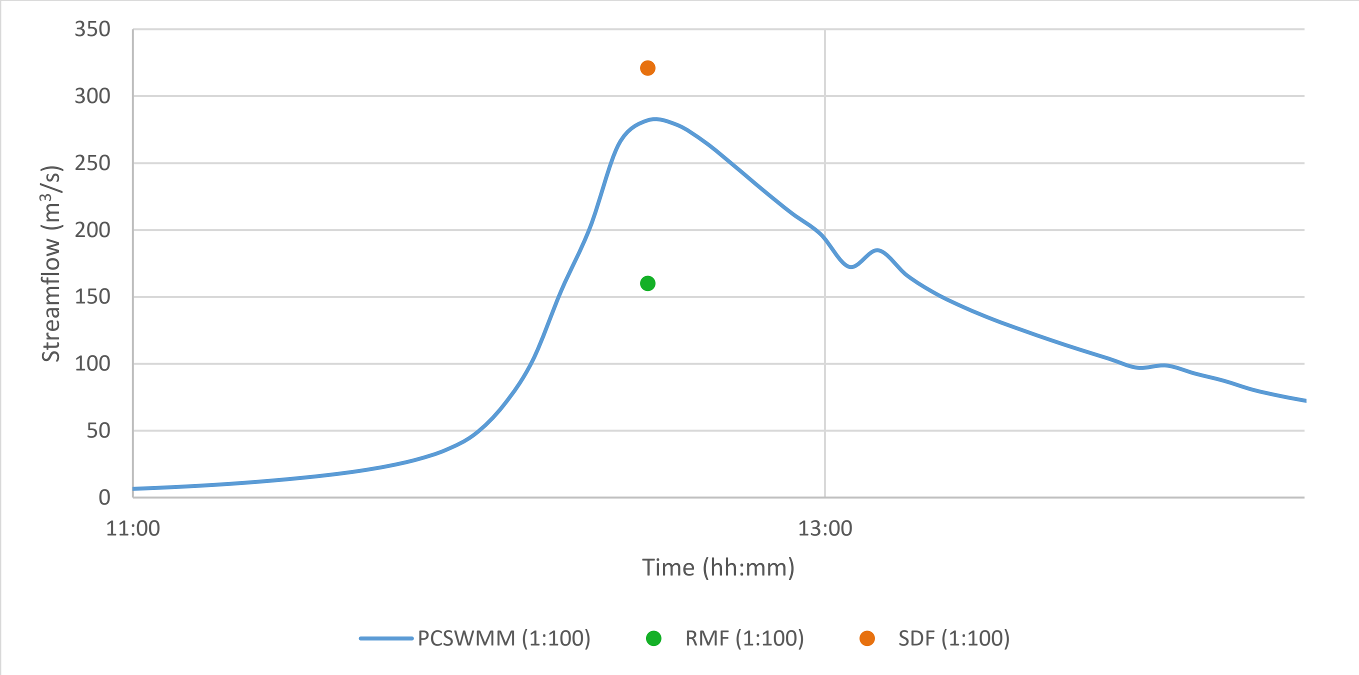

FIGURE A-1: 1:100 YEAR RI HYDROGRAPH FOR PRIMARY RIVER AND COMPARATIVE PEAK FLOWS

A.2 HYDRAULIC (FLOOD) MODELLING

The hydraulic model developed for modelling flooding needed to utilise available terrain data in the form of the 0.5m DEM and 25m DSM (for fringe areas).

A.2.1 HYDRAULIC MODEL CHOICE

HEC-RAS 6.3.1 was selected to model the hydraulic flooding on the two rivers of interest. HEC-RAS is designed to perform one-dimensional and two-dimensional hydraulic calculations for a full network of natural and constructed channels. The software is used worldwide and the 1D component of the model has been thoroughly tested through numerous case studies. The 2D component to the HEC-RAS model is a more recent addition having been released in 2015 although robust benchmarking (USACE, 2016) and verification and validation tests (USACE, 2018) have been performed to prove the 2D component of the model works as intended.

A.2.2 TOPOGRAPHIC DATA

The 0.5m DEM data (detailed in Section 2.3) provided the majority of the available terrain data for the hydraulic model build. This terrain data was reasonably detailed, although close inspection during the model builds concern related to the accuracy of the terrain data, particularly with the definition of the eastern river channel. Various other concerns have been noted in this report as they relate to the 0.5m DEM and concerns regarding the data's accuracy. Inaccuracy in the 0.5m DEM has a direct impact on the accuracy of the modelled flooding.

The use of the 25m DSM to supplement the 0.5m DEM results in fringe areas of the flood model which are not well represented given this coarse DSM data

A.2.3 COMPUTATIONAL MODEL MESH

In developing a 2D HEC-RAS model, it was necessary to first delineate the model boundary. The model boundary was then used to define the model grid, with a 10m model mesh spacing selected to maximise spatial detail while limiting unnecessary model complexity.

The computational model mesh is the primary element making up the HEC-RAS 2D model. This mesh contains the data about the terrain of the underlying elevation data, the presence of linear features and surface roughness.

One of HEC-RAS's major advances to hydraulic modelling has been the addition of a subgrid. The subgrid extracts the detail available in the underlying terrain (i.e. the 0.5 DEM) into a hydraulic properties table for each cell and cell face in the model mesh. This includes variables such as the elevation/volume relationship per cell and the cross-section, elevation/area, and wetted perimeter for each cell face. This results in HEC-RAS models being able to use a larger cell size while still representing much of the underlying terrain, thereby producing an improved model result.

Aside from added hydraulic detail, the visual benefit from HEC-RAS using a subgrid, is that a more representative result of the expected flooding is possible since HEC-RAS will show only partial flooding for a mesh cell (where applicable).

A.2.4 BOUNDARY CONDITIONS

Upstream and downstream boundaries were defined for the model using a normal depth slope. This 'normal depth' is estimated according to the river bed slope.

The three inflow hydrographs were applied to the upstream ends of the relevant river reachs within the hydraulic model, despite being representative of the accumulated flows at the downstream end of the respective reach. This is common practice, whereby the design hydrographs for a point at the end of a modelled river reach are applied to a point upstream and results in some conservatism (where more flooding is conservative).

A.2.5 ROUGHNESS VALUES

A Manning's 'n' value shapefile was developed for the site based upon a review of aerial imagery. Values ranged between 0.03 (river channel) to 0.13 (thick vegetation). Manning's 'n' values are approximate only and assume uniformity in areas (where some localised variation is expected).

A.2.7 MODEL RUN

More accurate full momentum equations were used in the running of the model. A stable model run was achieved.

A.2.8 ASSUMPTIONS AND LIMITATIONS

Various assumptions were required in the development of the hydraulic model with resultant limitations in the accuracy of the modelled flooding. They included the following:

- *PCSWMM parameterisation* – Design hydrographs estimated using PCSWMM are accurate given the potential for large deviations in their estimation to significantly influence resulting flooding.

- *Rainfall depth* – DRESSA rainfall depths are assumed accurate, with normal DRESSA values applied to this study. DRESSA also includes upper values representative of upper confidence limits.
- *Accuracy of terrain datasets* – the 0.5m DEM has been detailed in this report. Various concerns have been presented regarding its accuracy. Inaccaurcy in the 0.5m DEM will result in inaccuracy in the flood model results.
- *Culvert Dimensions* – culvert dimensions were approximated during the site visit. There is consequently some error expected. Absence of the eastern culvert (due to insufficient coverage of the 0.5m DEM) may underestimate flooding at the downstream section of the eastern river.
- *Mesh detail* – the default mesh utilised a 10m mesh size. While one of HEC-RAS's major strengths is the use of a subgrid, the obstructing or routing influence of linear features that are smaller than the mesh resolution will not be well defined.
- *Roughness values* – The selected Manning's 'n' values were representative of the areas they covered, including being representative regardless of the depth of flooding.
- *Model calibration* – no calibration of the model was undertaken as there is no observed data for calibration purposes.
- *Software Performance* - The software and methods utilised are assumed accurate with regards to their utilisation of input data and the processes they simulate.