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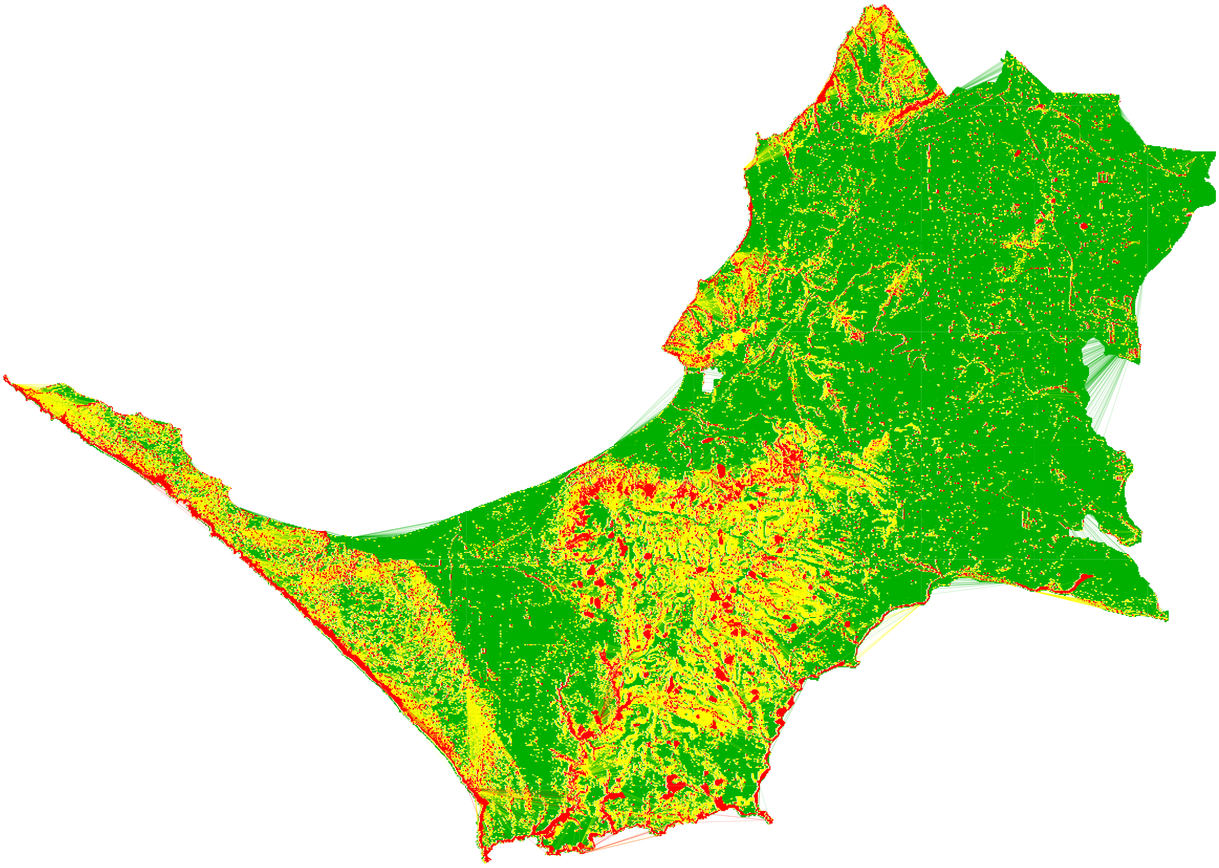

Draft for Comment Landslide Susceptibility Assessment, Stage 2

Mornington Peninsula Shire, Victoria

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Prepared for Mornington Peninsula Shire Council

DOCUMENT CONTROL

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DRAFT FOR COMMENT LANDSLIDE SUSCEPTIBILITY ASSESSMENT, STAGE 2

Mornington Peninsula Shire, Victoria

EXECUTIVE SUMMARY

INTRODUCTION

In 2000 the Mornington Peninsula Shire Council, which covers an area of approximately 730 square kilometres, commissioned a study to conduct a shire wide assessment of 'landslide hazards'. During the 1980's and 1990's a number of landslides occurred in areas of the Shire, resulting in considerable damage to dwellings, in some cases resulting in their demolition. While some individual detailed studies were undertaken (Coffey 1999 and others), there were many areas across the Shire that were not covered. In addition, the Council was being presented with geotechnical reports that were insufficiently detailed to assess the landslide risk or susceptibility. Detailed field studies were considered to be too expensive and a GIS approach was adopted. The Shire commissioned a study to assess the extent of landslip areas across the Peninsula. The assessment included preparation of parameter maps for geology, cadastre, digital terrain, landslides and standing groundwater depths for inclusion in a Geographical Information System (GIS) of the Mornington Peninsula.

The assessment recommended that the maps be combined with a review of numerous consultants' reports to enable the development of a map that classifies the Shire into areas of high, medium and low landslide susceptibility. Since the release of the initial report there have been significant improvements in the available GIS data.

The study was then expanded to make use of the newly available photogrammetric digital data, review and include the Council and consultants reports, produce a database of slope failures and generate a landslide susceptibility map and scope of geotechnical investigation for the Shire.

MORNINGTON PENINSULA GEOLOGY

The geology of the Mornington Peninsula and its relationship with slope stability is complex. There have been numerous papers and publications discussing the geology including Jenkin (1962, 1974, and 1988), Keble (1950), Gostin (1966), Neilson (1985, 1995 and 1999) and Dennis, Price & Miller (1993). The Geological Survey of Victoria 1:63 360 maps of the area were used for the distribution of the geological units present [Cranbourne (1967), Sorrento (1965) and Western Port (1967)]. Gostin (1966) mapped the coastal geology in the Mornington to Frankston coastal zone in detail.

The main geological units that are within the Mornington Peninsula and the effect of slope stability on those units is discussed below:

- Ordovician siltstone/sandstone rocks – Slope failures within the soils weathered from these rocks have been identified, especially in the very steep areas.

- Devonian Granitic rock - Deep seated failure in slopes within the granitic rocks has not been recognized. However the rocks are often highly jointed and prone to boulder failures in quarry excavations. Shallow failures in the weathered zone have also occurred.
- Tertiary Basalts of the Older Volcanics – Slope failures in these materials on hillsides are fairly widespread. It is the major source of slope instability on the Mornington Peninsula.
- Tertiary Fyansford Formation (Balcombe Clay) – The stability of this formation along the Port Phillip Bay coast and its relationship with slope failure of overlying geological formations is a major issue on the Mornington Peninsula coastline.
- Tertiary Baxter Sandstone – This formation is not regarded as a significant slope hazard, except when very steep. Generally failures of the Baxter Sandstone occur only as a result of failure surfaces in underlying geological units.
- Quaternary calcareous sands and Calcarenite (Pleistocene) –The variable degree of cementation in this deposit has a major impact on the stability as does the steepness, the height and degree of erosion by wind, rain and runoff.
- Coastal dunes, beach ridges, swamp and alluvial deposits (Holocene) – The dunes are not a major stability issue when undeveloped but can pose stability problems for construction if locally steepened. The swamp deposits can be softened and compressible but generally are located within creek confines.

There are other geological units, such as the Mt Martha sand beds, but these are minor and localised.

DIGITIZATION OF THE DATA

In order to develop the landslide susceptibility model it was necessary to digitise the available data into a GIS system. The data sets included in the model are as follows:

- Geology Zones

  As previously discussed, the geology of the Mornington Peninsula is complex. The Shire is covered by the three 1:63,360 geological maps, Western Port, Sorrento and Cranbourne, which were produced in the 1960's. The boundaries for the main geologies were digitised from the scanned maps. The different geologies defined for the study are discussed in Section 2.

  The spatial accuracy of the geological boundaries is unknown, but it would be reasonable to conclude that they would be no better than 100m.

- Identified Slope Failures

  The study of aerial photography identified numerous landslides across the Mornington Peninsula. The landslides were classified into 'possible' to 'certain' from aerial photography. All of the landslides were included in the study. However, further field and intrusive assessment of the sites will be required to confirm if the possible landslides are 'actual' as well as delineate the extent and features of the landslides.

- Landslide Susceptibility Studies

  There have been isolated studies of landslide susceptibility previously conducted for areas within the Mornington Peninsula Shire. The landslide susceptibility boundaries defined in those studies have been adopted in the current study. These studies have been used to validate the GIS model.

- Digital Terrain Model

  The Digital Terrain Model (DTM) for the model was initially based on photogrammetry (DSE CIP 2005-06) as it was the most comprehensive data available. This data was used for initial calibration of the susceptibility models and for development of the analysis code. While the photogrammetry data was fairly comprehensive it tended to 'average out' the slope gradients determined and therefore small sudden changes in gradient such as small cliffs, cut slopes and retaining walls were sometimes not clearly identified in the data.

As the study proceeded, more accurate LIDAR (LIght Detection And Ranging) data covering the whole of the Mornington Peninsula became available (DSE CIP 2006-07, 2007-08, 2008-09). This data, which was based on a 1m grid with 1 billion data points, was used for the final modelling.

The first step of adopting the LIDAR data for use in the susceptibility model was to determine its suitability for use and consistency between the different LIDAR data sets. While each data set was identified as having a vertical accuracy of +/- 0.1m, there were some discrepancies between co-located data sets of up to 2m. It was observed that most of the discrepancies occurred in heavily vegetated areas as a result of the vegetation. Where two sets of LIDAR data were available for a common point, the lower point was adopted. Single 'spikes' surrounded by lower points were also removed. Using these methods, the multiple LIDAR data sets were reduced to a single set of LIDAR data points with a 2m grid of approximately 250 million data points.

ESTABLISHMENT OF MODEL

The susceptibility analysis involves analysing the available data on an 8m grid over the whole of the Mornington Peninsula Shire. For each point on the grid, the following general methodology is adopted:

1. Determine if the point is within a previous study and adopt the previous value as appropriate;
2. Determine if the point is within a known certain or possible landslide and adopt a high susceptibility value;
3. Determine the geology of the point;
4. Determine the maximum slope gradient of all LIDAR 2m grid points within a 6m radius. The 6m radius was selected to ensure that any sudden changes in slope between each 8m analysis point were picked up. This ensures that the most conservative, i.e. steepest, slope in the vicinity of the point is used for the analysis and the impacts of nearby features such as cliffs, cuts and retaining walls were not missed.
5. Determine the average slope aspect of all LIDAR grid points within a 6m radius. This establishes the general orientation of the slope in the local area and allows directional bias to be used in the analysis;
6. Calculate the susceptibility value based on the geology, slope gradient and aspect.

In order to appropriately quantify the landslide susceptibility of a site, and place geotechnical investigation criteria on a site for a particular level of susceptibility, a classification system was developed to define the landslide susceptibility. This involves classifying areas in zones of low, medium and high landslide susceptibility. Based on inspection of various landslide sites in the peninsula and review of previous investigations, it was established that generally any two locations that have the same slope gradient, aspect and geology will often have the same susceptibility value. Therefore it is appropriate that for each particular geology a range of susceptibility values will apply to a range of gradients.

For the Balcombe clays and the rainfall, a minor aspect bias was included to accommodate the slope direction. The Balcombe clay bias is a result of the down warp of the Manyung fault (Nielson, 1995), while the southern faces are normally wetter with lower evapotranspiration effects.

Other site features such as variable rainfall, groundwater, rock depth and vegetation were considered for the analysis. However, while data is available regionally for these, the data on a local scale is sparse for varying topography and so was not used in the analysis.

The landslide susceptibility classifications of low, medium and high susceptibility were defined in the analysis as follows:

- Low Susceptibility (Green)
- Medium Susceptibility (Yellow)
- High Susceptibility (Red)

The boundary between low and medium susceptibility has been defined as the point beyond which creep or minor slope movement is likely to occur, but not necessarily a significant slope failure, without site modifications. The boundary between medium and high susceptibility has been defined as the point beyond which slope failures have either previously occurred or are considered possible based on previous studies and aerial photography. Landslide susceptibility weighting values are then used by interpolation between each data point to define the locations of the boundaries between the different landslide susceptibility zones.

Once the model was established it was verified against known landslides and areas of creep to confirm the validity of the model. For each geological area, localised susceptibility analyses were run for a number of known landslides or previous field studies. The results of the localised analyses were compared to the actual locations of the landslides. In general, the model predicted the locations of the susceptibility boundaries with reasonable accuracy when compared to the locations of the landslide head scarps and creep zones.

RESULTS OF THE ANALYSIS

Once the relationship between geology, slope gradient and aspect had been developed and verified, it was possible to conduct the analysis for the entire Mornington Peninsula Shire. The analysis involved the assessment of approximately 15.6 million locations across the Shire.

Polygons algorithms were developed to encapsulate the grid of results into polygons representing the various susceptibility zones. The output of the analysis was a map of the various susceptibility zones across the Shire.

CONCLUSION

This study has resulted in a map defining three different landslide susceptibility categories for the entire Mornington Peninsula Shire. The study will assist the Shire to more confidently assess slope stability issues for development on the Mornington Peninsula and to define the areas for different levels of geotechnical investigation.

The study does not eliminate the need for geotechnical investigations for each site and an individual landslip risk assessment will be required for a proposed development. An appropriate geotechnical investigation by an experienced geotechnical engineer or geologist may override the landslip susceptibility determined from the GIS.

The landslide susceptibility modelling is based primarily on the geology and the slopes, although other issues are also considered. Other important factors such as the depth to the groundwater, the presence of perched water table, vegetation and the depth to the rock were not able to be considered in this assessment and the assessment is based on typical conditions occurring in the study area. Consequently if there is shallow bedrock in the area of landslip, the susceptibility assessment is likely to be conservative. Conversely, if there is a perched water table or shallow groundwater, the predicted landslip susceptibility zones may underestimate the landslip susceptibility. A geotechnical investigation is still required for each site and an appropriate geotechnical assessment will always override this GIS study.

The assessment of the landslide susceptibility is based on the slope gradient, aspect and local geology as well as the research of numerous geotechnical reports conducted across the Shire. The spatial accuracy of the GIS system is limited to the accuracy of the 1:63,360 geology maps.

The assessment provides a rating for how susceptible a particular location is to landslides. It does not predict how a landslide at one location may affect another location. Therefore, this assessment does not include areas that may be affected by landslide run-out or landslide regression.

DRAFT FOR COMMENT LANDSLIDE SUSCEPTIBILITY ASSESSMENT, STAGE 2

Mornington Peninsula Shire, Victoria

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LIST OF ABBREVIATIONS AND UNITS

Technical Terms

1H:2V	Slope Ratio of 1 Horizontal to 2 Vertical
AHD	Australian Height Datum
AADT	Average Annual Daily Traffic
AC	Asphalt Cement
AMG	Australian Map Grid
Base Course	Upper Layer of the pavement
CBR	California Bearing Ratio (%)
CTCR	Cement treated crushed rock
DCP	Dynamic Cone Penetrometer
DTL	Daily Traffic Loading
EC	Electrical Conductivity
ESA	Equivalent Standard Axles
FoS	Factor of Safety
GIS	Geographic Information Systems
GPS	Global Positioning System
HDPE	High Density Polyethylene
HV	Heavy Vehicles (Usually a %)
LF	Loading Factor
LIDAR	LIght Detection And Ranging terrain data
NATA	National Association of Testing Authorities
PMB	Polymer Modified Binder
Prime	Application of a primer to a prepared base
Sub-Base Course	Lower layer of the pavement
Subgrade	Foundation material for the pavement
TDS	Total Dissolved Solids (salinity of water)

DRAFT FOR COMMENT LANDSLIDE SUSCEPTIBILITY ASSESSMENT, STAGE 2

Mornington Peninsula Shire, Victoria

1 INTRODUCTION

In September 2000 the Mornington Peninsula Shire commissioned Piper & Associates to conduct a shire wide assessment of 'landslide hazards'. The initial assessment was defined as 'Stage 1' and was completed in March 2002. The assessment included preparation of the following parameter maps for inclusion in a Geographical Information System (GIS):

- Geological Map
- Cadastre Map
- Digital Terrain Model
- Landslides identified from Aerial Photographs
- Standing Groundwater Depth

The assessment recommended that the maps be combined with a field mapping exercise and also a review of consultant's report to enable the development of a map that classifies the Shire into areas of high, medium and low susceptibility with regard to landslides. This further work was described as Stage 2.

Since the release of the initial report there have been significant improvements in the available GIS data and also computer power allowing the analysis of landslide susceptibility to be able to be conducted by a computer to reduce the engineer's or geologist's time in the field.

In a letter dated 18th April 2007, Mornington Peninsula Shire Council requested that Lane Piper prepare a fee proposal for Stage 2 of the assessment. Lane Piper prepared the fee proposal (207166Proposal01.2 dated 18 May 2007) that recommended the following approach:

7. Make use of the available photogrammetric digital data
8. Enhance the information with fieldwork
9. Review and include the Council and consultants reports
10. Produce a database of slope failures
11. Develop a logic sequence or algorithms for assessing the susceptibility
12. Generate a landslide susceptibility map and scope of geotechnical investigation for the Shire

At the time of the Shire commissioning the assessment, the Australian Geomechanics Society released their guidelines for Landslide Risk Management in *Australian Geomechanics, March 2007*. The guidelines provide a framework for assessing landslide susceptibility for a region. The recommendations of these guidelines have been incorporated into this assessment.

Since the commissioning of the assessment, further more accurate data has been made available for use in assessing the landslide susceptibility. This data has been incorporated into the analysis methodologies.

2 PROJECT HISTORY

In the past three decades, the Shire and its residents have experienced difficulties and expense as a result of slope instability issues throughout the Shire. These instabilities have varied from minor slope failures in rural areas to a few cases where the dwellings have had to be demolished. With increasing intensity of development of the Shire, particularly along the coastlines, the implications of slope instabilities are becoming greater. Increased flow intensity of creeks and drainage lines due to development are also contributing to the slope instability of those creeks and drainage lines.

Cardno Lane Piper has been involved in the assessment and remediation of a number of these slopes. Some of these areas include:

- Ballar Creek, Mt. Eliza
- Two Bays Road, Mt. Eliza.
- Gunyong Creek, Mt. Eliza
- Davey's Bay, Mt Eliza
- Hearn Creek, Mt. Martha
- Tanti Creek, Mornington
- Spindrift Avenue, Flinders
- Sunnyside Road, Mornington.
- The Esplanade, Mornington
- Mount Martha North Beach
- Ellerina Road, Mount Martha
- Latrobe Parade, Dromana
- Anthony's Nose, Dromana
- The Eyrie, McCrae
- The Sister's, Sorrento
- Boneo Road, Flinders

A number of residences have been constructed in areas that are undergoing slope instability or within old slope failures.

The onus is on the Shire to accept responsibility for the approval of a sub-division in the event of a landslide as in the case of Ballar Creek. However, over large sections of the Shire, the possibility of a landslide is remote and to impose stringent requirements on all proposed sub-divisions or works would be a considerable and unnecessary impost on the community.

The Shire does appear to have to accept some responsibility for the damage if a significant landslide should occur, whether or not a site classification for the particular dwelling is carried out by a soil tester. The soil tester classifying the site for AS2870 "Residential Slabs and Footings" often does not have the expertise to assess the site for the potential for land slippage. The Shire has potential liabilities, possibly considerable if a significant landslide should occur. However, in many areas of the Shire such as in the sand dunes behind Sorrento, there is little risk of a landslide apart from localised steep dunes or excavated batters. The study does not propose to address the localised stability of the site as a result of construction as there are adequate measures already in place to handle this.

3 PROPOSED ZONATION OF THE SHIRE

The normal approach taken by other Shires and Authorities is to zone the Shire into areas of potential landslide susceptibility. It is important to understand that the purpose of the zonation is not to determine the risk that the site will undergo a landslide, but to rank the areas of the Peninsula into areas of susceptible to landslides. It is proposed that the Shire be zoned into three areas of landslide susceptibility, namely:

- High
- Medium
- Low

Each of the three different susceptibility zones is to have a different level of geotechnical investigation that is required in order for further development of a site within that zone to occur.

This zoning of the Shire into areas of landslide susceptibility allows the following:

- The proposed residents, developers and Council can assess their risk in building and developing certain areas
- The Shire's personnel can make a more definitive assessment as to whether to approve the development or ask for additional geotechnical investigation
- The Shire's exposure is reduced as the decisions are based on geotechnical and geological expert opinion
- The Shire's other assets can be assessed for landslide susceptibility
- Responsible development is encouraged and provides information to developers
- Provides guidelines for the building surveyors and engineers to issue building approvals
- Outlines the extent of geotechnical investigation and assessment for development within the Shire
- Provides a system for updating the information and maps as it becomes available
- Provides a system that can be integrated into a GIS for the entire Peninsula.

It is important to understand the definition of several terms which are provided in AGS(2007):

- ***Landslide.*** *The movement of a mass of rock, debris or earth down a slope*
- ***Landslide Susceptibility.*** *A quantitative or qualitative assessment of the classification, volume (or area) and spatial distribution of landslides which exist or potentially may occur in an area. Susceptibility may also include a description of the velocity and intensity of the existing or potential landslide*
- ***Hazard.*** *A condition with the potential for causing an undesirable consequence. The description of landslide hazard should include the location, volume (or area), classification and velocity of the potential landslides and any resultant detached material and the probability of their occurrence within a given period of time. Landslide hazard includes landslides which have their source in the area or may have their source outside the area but may travel on to or regress into the area*
- ***Risk.*** *A measure of the probability and severity of an adverse effect to health, property or the environment. Risk is often estimated by the produce of probability and consequences. However, a more general interpretation of risk involves a comparison of the probability and consequences in a non-product form.*
- ***Zoning.*** *The division of land into homogeneous areas or domains and their ranking according to degrees of actual or potential landslide susceptibility, hazard or risk*

The system will allow a Council officer to access the GIS system on their computer to determine the landslide susceptibility ranking for a property as the digital Cadastre survey of the Shire will be overlain with the digital hazard zonation map.

The study will zone the Shire according to the following framework:

Table 3-1: Landslide Susceptibility Zonation Framework

Landslide Susceptibility	Explanation	Implication for Development
High	Evidence of active or past landslips or rock or soil failure; extensive instability may occur. Evidence of significant soil creep or minor slips or rock face instability; significant instability may occur during and after extreme climatic conditions.	Strict development restrictions and/or geotechnical works required. Extensive geotechnical investigation necessary. Risk after development may be higher than usually accepted.
Medium	Evidence of possible soil creep or a steep soil covered slope; significant instability can be expected if the development does not have due regard for the site conditions.	Some development restrictions required. Moderate level of geotechnical investigation necessary. Risk after development normally acceptable.
Low	No evidence of instability observed; instability not expected unless major site changes occur.	Good engineering practices suitable for hillside construction required. Risk after development normally acceptable. Typical site classification required.

The risk to persons and property will need to be determined for each individual property for the particular proposed development and can only be determined after an appropriate geotechnical investigation and assessment for the particular property. Onsite investigations and assessment may alter the assessment of the landslip susceptibility and appropriate and detailed onsite investigations should override the GIS assessment.

3.1 Methodology

As previously discussed, the purpose of Stage 2 of the assessment is to build on the foundations established in Stage 1 of the assessment and create a series of GIS maps that allow the Council officers to assess the landslide susceptibility of a particular site and allow them to make decisions on potential developments and the adequacy of the geotechnical investigations.

Stage 1 of the assessment was primarily a “desk top” study that gathered together all of the relevant information and reports, such as:

- Cadastre Survey
- Topographic Information
- Geological Data and Reports
- Aerial Photographs
- Rainfall and hydrogeological data
- Reports by other geotechnical consultants in the Shire’s records.
- Reports by Melbourne Water, Universities and other Government Departments.

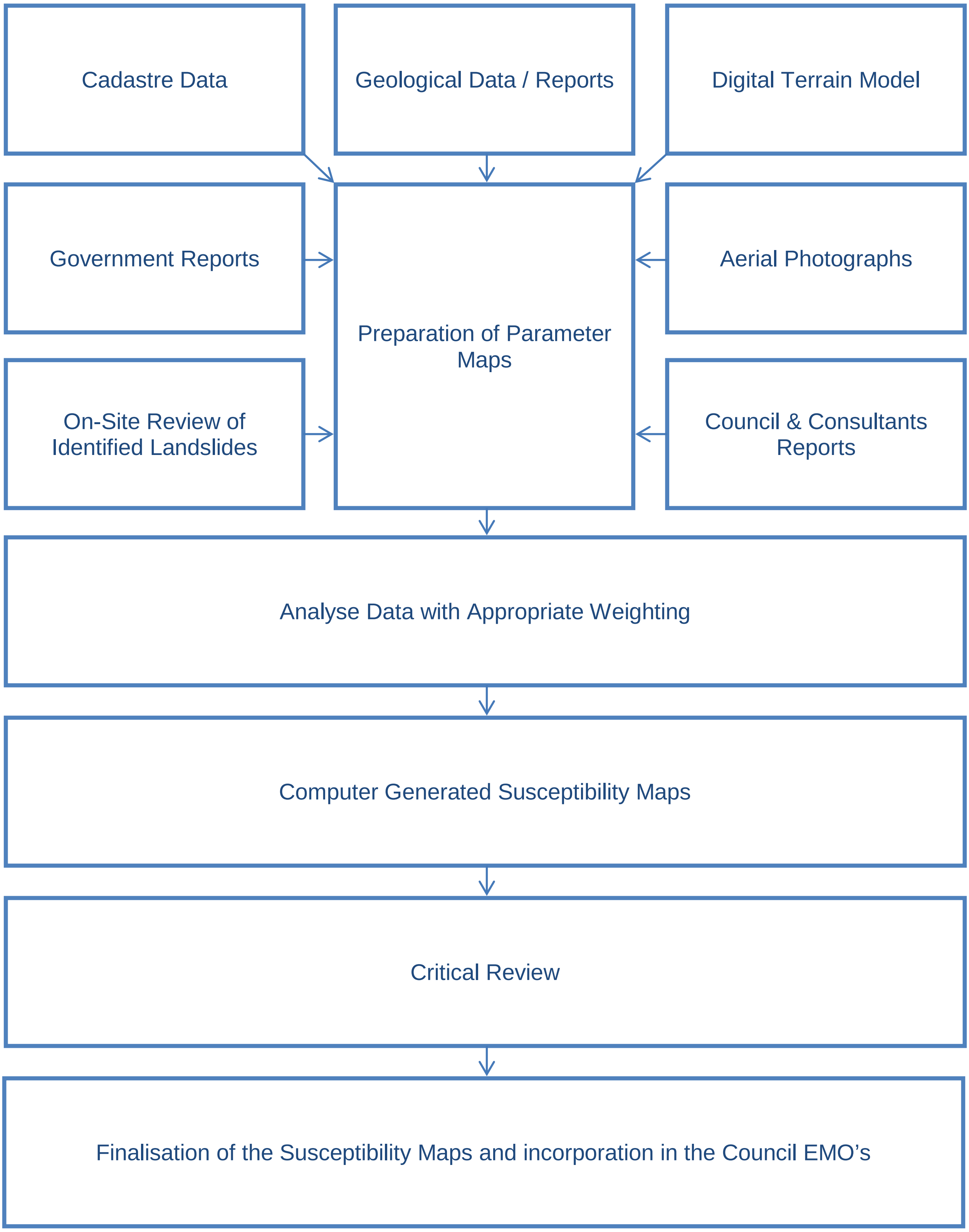
The desktop study allowed the production of several GIS maps which are already in use by the Shire.

This Stage 2 assessment involves further developing the existing maps and also creating a GIS enabled database of existing literature pertaining to landslides within the shire.

The GIS software MapInfo will then be used to interrogate the various inputs and determine the landslide susceptibility zonation system.

Once the information is all collected it has to be complied and recorded in an appropriate manner to allow the findings and zoned map of the Shire to be presented and allow updating of the map as further information becomes available in the future.

The proposed methodology is shown in the following chart:


Cadastre Data
Geological Data / Reports
Digital Terrain Model
Government Reports
Preparation of Parameter Maps
Aerial Photographs
On-Site Review of Identified Landslides
Council & Consultants Reports
Analyse Data with Appropriate Weighting
Computer Generated Susceptibility Maps
Critical Review
Finalisation of the Susceptibility Maps and incorporation in the Council EMO's

4 EXISTING COUNCIL EMO'S

There are presently five existing EMO's in place for the Mornington Peninsula Shire. These are:

- EMO1 – Erosion Prone Slopes
- EMO2 – Unstable Slopes
- EMO3 – Ballar Creek
- EMO4 – Medium Landslip Susceptibility for Flinders and Tanti Creek
- EMO5 – High Landslip Susceptibility for Flinders and Tanti Creek

EMO1 and EMO2 were developed in the early 1970's by the Westernport Regional Planning Authority. There is no record of the method used to establish these EMO's and the accuracy of the boundaries encompassing the EMO's is also unknown. To our knowledge, these EMO's have not been used by the Council in recent decades.

In 1999, Mornington Peninsula Shire Council introduced EMO3 for the area in the vicinity of Ballar Creek, Mount Eliza. The EMO was based on a Coffey Geosciences report (Coffey, 1999) which provided a detailed assessment of the landslide potential at Ballar Creek. The report introduced the need for appropriate geotechnical assessments of any potential developments in the EMO. The Coffey report provided for four different landslide susceptibility categories which were integrated into the EMO as a single EMO category.

In 2009, Council introduced EMO4 & EMO5 for the Flinders township and also the area in the vicinity of Tanti Creek, Mornington. These EMO's were based on previous landslide susceptibility assessments by Lane Piper (2008A and 2010B). These two reports classified the study areas into areas of high, medium and low landslide susceptibility. EMO4 was based on the medium susceptibility zones in these studies while EMO5 was based on the high susceptibility zones. Development constraints and recommended levels of geotechnical investigation were included as part of the EMO's.

5 GEOLOGICAL LITERATURE SURVEY

This literature survey of current available geological reports forms part of a study of the factors involved in slope stability across the Mornington Peninsula carried out to assist with planning by local government. Its aim is to gather together known information on geology and geotechnical issues in relation to slope stability as a prelude to further study on these issues.

A wide range of published literature has been consulted together with published Geological Survey of Victoria maps of the region. Relevant unpublished reports of the Geological Survey of Victoria have been examined, together with some unpublished reports from the former Melbourne and Metropolitan Board of Works and the former State Rivers and Water Supply Commission. At the time of writing this report, no significant information was available from VicRoads. Several research theses from universities in Melbourne were found with information relevant to slope stability issues in the Mornington Peninsula. There are a number of private consultant's reports within the Shire records and other available reports from consultants were also studied.

The available information on slope stability is inadequate. Many geologists who have studied the Mornington Peninsula have given little or no attention to slope stability issues. However, the geologists do point to some areas of concern with slope stability and suggest other areas apparently free of slope problems.

This report discusses slope stability as it relates to the geological units present in a sequence based on geological age. Minor geological formations, which have no bearing on slope and coastal stability, are not mentioned.

5.1 Geological Structure

Jenkin (1974, 1988), building on the work of Keble (1950), defines the basic geological structure. The higher ground on the Mornington Peninsula is an upwarped spine of basement rock comprising Ordovician and Silurian mudstones and sandstones folded into a broad anticlinal structure with subsidiary folds and intruded by several masses of Devonian granitic rocks. Trending approximately NE-SW, this spine is known as the *Mornington Block*.

The *Mornington Block* is bounded on the west by the *Selwyn Fault*, the dominant fault affecting the Mornington Peninsula and the one with the greatest displacement. It extends as a line a little off-shore from Frankston to Dromana then crosses the Peninsula in a southerly direction to reach the Bass Strait coast about 3 km NNW of Cape Schanck. It is clearly marked by gravity anomalies as a deep-seated structure on the Queenscliff 1: 250 000 Bougher Anomaly map (Bolger, 1977). The Selwyn Fault has a displacement of about 300 m (Keble, op. cit.) on its down-warped western side. This down-warped surface is known as the *Port Phillip Sunkland* (Keble, op. cit.) and includes the dune-covered *Nepean Peninsula* (Keble, op. cit.) stretching from near Rosebud and Cape Schanck to Point Nepean. Contrary to expectation, the Selwyn Fault was not encountered in the Dromana Tunnel of the South Eastern Effluent Outfall south of Rosebud. However, Thornton (1972) believes that it is present there in older rocks covered by young soft ground sediments through which the tunnel passes.

The eastern edge of the *Mornington Block*, in contrast, is marked by minor down-warping. Keble (op. cit.) regarded this down-warping to have occurred along a fault with about 60 m displacement, which he named the *Tyabb Fault*. However, Bolger (1977) found no clear evidence for this fault as he demonstrated a lack of sub-surface displacement of beds across the supposed fault alignment. A broad monoclinal warp rather than a fault is indicated at the eastern edge of the *Mornington Block* and is probably the southward continuation of the *Clyde Monocline* (Jenkin, 1962), as Bolger (op. cit.) surmised.

Eastwards of the zone of warping at the eastern edge of the *Mornington Block* is the depressed low-relief landscape of the *Western Port Sunkland* (Jenkin, op. cit.), capped by Tertiary sandy materials overlying mainly Silurian bedrock. The *Mornington Block* is flanked and veneered by Lower Tertiary basaltic rocks (*Older Volcanics*) and several units of almost flat-lying Tertiary sedimentary materials.

The NW-SE trending Flinders Fault (Keble, op. cit.) has no topographic expression, but down-warping southwards of this flexure enabled the accumulation of thick basaltic materials (*Older Volcanics*) in early Tertiary time.

The greatest relief and deepest dissection are found between Frankston, Flinders and Cape Schanck, with granite forming the most prominent high points of Arthur's Seat, Mt Martha and Mt Eliza. South-east of Mt Eliza the landscape is more undulating and the depth of dissection less.

Reference should be made to Jenkin (1988, Fig. 14-6.1) for the location of faults and to the following Geological Survey of Victoria 1:63 360 maps for information on the distribution of the geological units present: Cranbourne (1967), Sorrento (1965) and Western Port (1967). Gostin (1966) has mapped the geology in the Mornington to Frankston coastal zone with more detail than shown on the Geological Survey maps.

5.2 Faulting, Earthquake Hazards (Seismicity) and Slope Stability

The triggering action of earthquake shock waves in the genesis of landslides, slumps, rockfalls and earthflows on certain slopes is discussed and documented by Wieczorek (1996) and many others. He notes situations of water saturation, disaggregated soils or rock, soils of low cohesion and build-up of pore water pressures with attendant lowering of soil shear strength as conditions which can lead to slope failure under the impact of earthquake shaking. Pleistocene Dune Sands discussed later in this report are susceptible to seismic activity due to their lack of cohesion but are typically not saturated.

Though slope failures are known on the Mornington Peninsula, the absence of dating for any of these leaves no basis for possible correlation of them with recorded seismic events. Documented seismicity on the Mornington Peninsula is given below.

Gregory (1912) records earthquake shocks affecting the Mornington Peninsula as listed beneath, with their intensities given by Underwood (1972) on the Modified Mercalli Scale (Richter, 1958).

- January 10, 1885, felt at Cape Schanck, Mornington and Berwick. - Intensity 2-3
- June 7, 1891, felt at Sorrento and severely at Rosebud - Intensity 4
- December 23, 1892, shocks noted at Mount Martha, Cape Schanck, Mornington and Flinders – Intensity unknown

Additional earthquake events recorded by Underwood (1972) are listed below within the period 1841-1966.

- March 28, 1909, felt at Flinders – Intensity unknown
- September 2, 1932, felt at Mornington – Intensity 4.5 (Gibson et al., 1981) – discussed later (Holmes, 1933)
- July 5, 1966, felt south of Cape Schanck – Intensity 4.1
- November 15, 1966, felt west of Cape Schanck – Intensity 2

The earthquake intensities on the Modified Mercalli Scale shown above are all low to moderate. An intensity of 2 is rarely felt by people and an intensity of 4 feels like a truck hitting a building but causes no damage to the structure (Gibson and Peck, 1992).

The records reported above are not complete, as discussed by Underwood (op. cit.). His work and that of Gibson, Wesson and Cuthbertson (1981) reveals that the Mornington Peninsula is one of the less seismically active regions of Victoria.

The only epicentre located for any seismic event was for the Mornington earthquake of 1932 (Holmes, 1933): significantly, elliptically shaped isoseismic lines came to a focus of maximum intensity along a line closely approximating with the Selwyn Fault, pointing to stress release along the fault alignment but no accompanying strain during seismic events has been observed. The other earthquake events indicated above may also relate to the Selwyn Fault.

No conclusion can be reached on whether seismicity may have triggered some slope failures on the Mornington Peninsula, as already stated, though lack of any evidence for major slope weaknesses makes this unlikely. Future seismicity might induce failures in any potential areas of major slope weakness not yet identified, but it is at present impossible to give any evaluation of this possibility in the absence of field studies. However, it is more likely that any seismic activity would aggravate any existing landslides and may create landslides in any over steepened loose sand deposits.

5.3 Ordovician Rocks

These are the oldest rocks on the Mornington Peninsula and are found in its central part, to be overlain by Tertiary basalt (Older Volcanics) to the south and irregularly to the north of the central part of the Peninsula by a dissected sheet of Tertiary sandy materials from the Baxter Sandstone.

The Ordovician rocks comprise blue and white silicified shales, light coloured sandstones, shales, mudstones and minor thin quartzite bands, together with some dark grey fossiliferous shales (Jenkin, 1974), which enabled Keble (1950) to distinguish different age groups within these rocks. They are hard rocks free from significant weathering. Mapping has not established the detailed occurrence of the various rock types present throughout the area. Intrusions of granitic rocks have silicified and partly re-crystallized the nearby Ordovician rocks to produce extremely hard contact zones, as at the Moorooduc Quarry (Neilson, 1999a) where hornfels is developed adjacent to the Mt Eliza granite. The outcrop is not good and revealing exposures are mostly in quarries.

A broad anticlinal structure with its axis about 2 km east of Moat's Corner, eastward of Dromana (Keble, op. cit. and Jenkin, op. cit.) is the main structure affecting the Ordovician beds, with additional minor folds adding complexity. Bedding planes appear to be the main discontinuities governing rock mass stability rather than jointing in the Moorooduc Quarry (Neilson, op. cit.) and this may be general over the Peninsula but the published data does not allow a general conclusion to be drawn on this issue.

Data on rock weathering is largely lacking. The light colours common with these rocks suggest a moderate degree of weathering, but the depths at which residual soils (engineering soils) and highly weathered rock yields to hard rock is little known. The photographs shown by Keble (q.v.) from quarries suggest that residual soils are quite thin, though no general conclusions can be drawn from this. The Devilbend dam site located 6 km west of Hastings revealed silicified units of siltstone and chert interbedded with shale, siltstone, sandstones and black carbonaceous shale, all with steep easterly dips (Currey, 1965) and importantly, the mudstones and sandstones were weathered to rather soft engineering soils (probably largely residual) to depths of between 11m and 15m. The silica-rich beds at the Devilbend damsite, in contrast, though weathered to depths of between 0.9m and 9m, remained hard rock though quite fractured. The thickness of the weathered mantle is probably quite variable across the Peninsula.

Clay bands and iron oxide minerals were found in some bedding planes and joints at the Moorooduc Quarry (Neilson, op. cit.) where they influence rock mass stability. Clay was found in joints at the Devilbend damsite (Currey, op. cit.).

The literature contains no reference to slope failures in the Ordovician rocks. This does not necessarily mean that slope failures are absent and raises the possibility that they might have escaped observation. The 1: 63 360 Western Port Geological Survey map (1967) contains symbols suggesting scarps - which may be slope failures of some kind - in the hilly landscape crossed by Bulldog Creek, Tubbarubba and Devilbend Creek. These apparent scarps cannot represent the outcropping of very hard siliceous beds as the scarps are mostly sub-horizontal and the beds are steeply dipping. Their possible origin as slope failures remains, with considerable slope steepness and strong weathering extending to maximum depths of 11 to 15 m found at the Devilbend damsite (Currey, op. cit) as enabling factors.

The steeper landscapes in Ordovician rocks are therefore regarded as having possible slope failure risk, which should be evaluated by study of aerial photographs and appropriate geotechnical investigation.

5.4 Silurian Rocks

The Silurian rocks are found in the western part of the Mornington Peninsula and commencing near Bittern, extend northwards as part of a gently undulating landscape. They comprise beds of light coloured shales, mudstones and sandstones, with the hard siliceous beds found in the Ordovician sequence uncommon (Jenkin, 1974). Clear data on rock weathering is lacking. Structural data is sparse. Jenkin (op. cit.) regards the Silurian beds as being apparently conformable with the Ordovician beds, which they overlie.

The literature records no slope failures in these rocks though this cannot be certain. However, given the low relief of the landscape in which the Silurian rocks are found, it is considered that there is minimal risk of slope failure in these rocks.

5.5 Granitic Rocks (Devonian)

Three separate masses of granitic rocks are found in the Mornington Peninsula. These are the *Dromana Granite*, the *Mount Martha Granodiorite* and the *Mount Eliza Granodiorite* (Jenkin, 1974), named after their main centres of occurrence.

The ***Dromana Granite*** is a hard medium-grained rock composed of quartz, the feldspar minerals orthoclase, perthite and oligoclase together with biotite (Jenkin, op. cit.). The petrography and associated granitic dykes are described by Baker (1938). Starting at the coast at McCrae, this granitic mass rises steeply to the eminence of Arthur's Seat where it is capped by a small area of Devonian dacite. It is characterized by fairly steep slopes. South of Arthur's Seat the granitic land surface is unevenly covered by Tertiary basalts (Older Volcanics).

Weathering of the *Dromana Granite* has been little studied. Information on weathering is largely confined to data gained from the investigation and construction of the South Eastern Effluent Outfall, which is known as the Dromana Tunnel where it passes through this granite beneath Arthur's Seat.

The Dromana Tunnel laterally intersects 6 km of this granite, with a maximum cover of 260m beneath Arthur's Seat. Thornton (1992) records that moderately weathered granite predominates in the tunnel with "only a comparatively short section of about 900 m of dominantly slightly weathered rock". He also found at irregular intervals in the tunnel some weaker highly weathered areas and other areas of highly to extremely weathered rock associated with crushed and sheared zones and recorded three main joint sets. A detailed record of the tunnel (Thornton, 1972) showed a zone of hornfels from the metamorphism of Ordovician rocks south of Rosebud which does not outcrop. A thickness of about 18 m of residual granitic soil (sandy clay and clayey sand) above hard but quite weathered granite was found in investigation bores along the tunnel alignment south of Rosebud (Neilson, 1966). Approximately 15 m of sandy clay and clayey sand (possibly Tertiary in part) above the hard granite was also found to be common from these bores along the Dromana Tunnel alignment.

At Red Hill, Brumley (1978) in an appraisal of slope stability noted about 3 m of granitic sand above slightly weathered granite and observed that though such granitic soils are susceptible to erosion, landslides are not found in them. It is noteworthy that granitic soils and highly weathered granite erode readily.

The area covered by the *Dromana Granite* is commonly steep and the cover of residual soils and highly weathered rock can be expected to be of very variable thickness. A concurrence of steep slope – either natural or through recent erosion - water saturation and a thick weathered profile could lead to slope failure. However, no references to any slope failure in granitic rocks were found in the literature.

The ***Mount Martha Granodiorite*** is a medium grained rock composed chiefly of quartz, the feldspar minerals oligoclase and orthoclase, abundant biotite mica and some hornblende (Jenkin, 1974). It is in contact with the Ordovician bedrock, which it intrudes, in a hilly landscape in which no slope failures have been reported. Keble (1950) records that it is grey when fresh but takes on green and pink colours when weathered.

The granodiorite is exposed well along the coast, where it is commonly stained pale brown. Broad shore platforms about 25 m wide occur south-east of Martha Point, sloping gently seawards from the cliffs behind, the rock is more deeply weathered at the northern and southern margins and fresher north of Martha Point (Rosengren, 1988) and further north, a 30m wide shore platform in moderately weathered rock on both sides of Balcombe Point extends below the cliffs. The granodiorite is well jointed (Keble, op. cit.). The cliffs show variable weathering and are capped by a micaceous clayey sand close to Balcombe Point (Neilson, 1999b); they appear to be stable and only undergoing quite slow erosion, with minor rockfalls as the most probable slope hazard.

The ***Mount Eliza Granodiorite*** is typically grey and composed mainly of quartz, the feldspar minerals plagioclase and orthoclase, biotite and some hornblende (Jenkin, 1974). It intrudes the Ordovician bedrock, with a contact about 500 m east of the Mt Eliza eminence. The Moorooduc quarry nearby reveals the Ordovician rocks transformed to hard quartzites and quartz – mica rocks (Skeats, 1907) near the granodiorite.

A varied topography has been eroded into the Mount Eliza Granodiorite and partly filled by a blanket of the Tertiary Baxter Sandstone and towards the coast the granodiorite is directly overlain in parts by the slightly older Tertiary Fyansford Clay (Balcombe Clay). The surface topography in the granodiorite is undulating rather than steep. The variability in weathered condition along the coast, as noted below, is likely to be found throughout the mass. There is no known record of slope failure in the *Mount Eliza Granodiorite* and closer examination would be expected to confirm this.

The granodiorite outcrops along the coast as shown by Gostin (1966), from c. 240 m northwards of Sweetwater (Tangenong) Creek to Landslip Point at Olivers Hill. It is absent from Landslip Point until close to Kackeraboite (Naringalling) Creek, 150 m southward of which it ends. The coastal cliffs with granodiorite range from granitic clay to hard slightly weathered rock, with erosion variable and concentrated in the more weathered materials; limited parts are under substantial marine erosion (Dennis, Price & Miller., 1993). Further south in the Sunnyside Beach area, granitic rock is found in shore platforms (Rosengren, op. cit.) and cliffs within hard rock (Gostin, 1966).

5.6 Basalt of the Older Volcanics (Lower Tertiary)

Basaltic materials of the *Older Volcanics* form the next geological unit in order of age which is important in the consideration of slope stability. They overlie an uneven landscape of granitic rocks and Ordovician sedimentary rocks together with thin scattered Tertiary sands and clays of no significance to the present study.

Commencing in the north along an irregular E-W line through Arthur’s Seat, the basaltic materials have been sculptured into a hilly landscape with many fairly steep slopes which decline in elevation southwards. Outcrops of the older rocks protruding through the volcanic materials up to about 5 km south of Red Hill indicate only moderate thicknesses of the Older

Volcanics in this area, but influenced by the Flinders Fault, the thickness increases greatly southwards and Keble (1950) records bores showing the thickness of the volcanics exceeding 390 m at Flinders and 259 m at Cape Schanck. The surface and sub-surface distribution of the Older Volcanics in the Mornington Peninsula and Western Port region is shown by Jenkin (1962).

The volcanics are composed of flows of olivine basalt, together with agglomerates, tuffs and tuffaceous sediments and also prominent clays derived from the weathering of all these materials (Jenkin, 1962, 1974). Gostin (1964) shows that the clays produced by weathering contain montmorillonite and kaolinite, with halloysite present in some samples. The capacity of montmorillonite to absorb considerable water and weaken and its thixotropic character can lead to slope instability where it is significant in a slope.

The cliffs between Flinders and Cape Schanck reveal flat-lying red earthy clay horizons of fossil soils extending for kilometres between flows of dark hard basalt, with ten flows exposed in 91 m at Cape Schanck (Keble, op. cit.). The bores at Flinders and Cape Schanck record major thicknesses of clays and decomposed basalt in addition to hard basalt. Neither in the outcrops between Flinders and Cape Schanck nor in the two bores above are there any intercalations of sedimentary material (Keble, op. cit.).

The basalt flows are jointed in many patterns including columnar joints (Bird, 1993); Fethers (1979) notes siderite cementing columnar joints at Flinders and Cape Schanck.

The thickness of residual clay soil capping the weathered mantle and the patterns of weathering have been little studied. The Flinders bore shows 7 m of clay over “decomposed” basalt whereas there was no residual clay at the Cape Schanck bore (Keble, op. cit.). Near the head of a branch of Main Creek in the Main Ridge area, 9 m of hard clay was found to overlie moderately weathered basalt (Neilson, 1998a). Brumley (1978) notes that in the Red Hill area at least 4 m of brown and buff firm to stiff clay form the top of the basaltic weathering profile. Throughout the area of the Older Volcanics surface residual clay of variable thickness is probably common.

Landslides have been recognized in the terrain of the Older Volcanics. The 1; 63 360 Sorrento Geological Survey map (Jenkin, 1965) shows a landslide near the head of Main Creek in the Red Hill area and the adjoining 1: 63 360 Western Port map has many symbols indicative of scarps and slope failures from the Western Port coast towards Red Hill South. Brumley (op. cit.) reports that landslides are “relatively common” in the residual basaltic clay soils, locates two old landslides between Red Hill South and Red Hill and comments that there are no signs of recent movement on the old slides. An active landslide 1.2 km north of the jetty at Flinders has been studied (Neilson, 1998b). Extensive slumping at the top of the cliffs at Shoreham has obscured a sequence of basalt flows (McLaughlin, 1977).

A small occurrence of weathered basalt on the Port Phillip Bay coast between Landslip Point and Daveys Bay plays no role in coastal stability.

The coastline between Balnarring Beach and Flinders shows cliffs and headlands with wide shore platforms exposed at low tide, all cut into the Older Volcanics. Beaches of quartz sand and basalt shingles lie on the shore platforms and partly cover them. The basalt is generally brown and fairly weathered (Bird, 1993). Drilling from the cliff top near the Flinders Jetty ceased at 9.4 m in continuous basaltic clay (Neilson, 1998c). Erosion of the cliffs is not pronounced and Jenkin (1974) observes that the cliffs facing Western Port Bay are less steep and more vegetated than those facing the open ocean, but it is a coastline undergoing slow erosion (Jenkin, 1962). The bluffs along this section of coast contain local slumps and West Head, Flinders, shows slump scars in weathered basalt (Bird, op. cit.) and a slump in

Pleistocene clayey sands and clays overlying the basalt at West Head has been studied (Cecil, 1985).

The high energy coast from Flinders to Cape Schanck is crenulated, with higher and steeper cliffs than those in Western Port Bay and the basalt is commonly dark grey and fresher than in the cliffs at Western Port Bay (Jenkin, 1974). Pocket beaches are almost entirely of basalt shingles and cobbles. Steep cliffs, rock stacks on wide shore platforms and the crenulated coast attest to active marine erosion and are further described by Bird (op. cit.). Rock falls occur and some unrecognized slumping is likely to have taken place on cliffs with more weathered volcanic materials.

5.7 The Fyansford Formation or Balcombe Clay (Tertiary: Miocene)

The *Fyansford Formation*, described by Gostin (1966), is a pale grey to dark grey stiff to very stiff silty clay and clayey silt, with a minor fine-grained quartz sand content in some areas. It contains calcareous marine micro-fossils and larger fossils, together with calcareous nodules. Where exposed, the nodules and fossils tend to be leached out and a pale brown colour develops. It contains montmorillonite, the weakening effects of which have been described in the Older Volcanics section of this report. The formation is generally fissured, of high plasticity and dips at low angles, even though it is poorly bedded.

This geological unit is found in outcrops intermittently along the coast between Landslip Point on Olivers Hill near Frankston and a point about 1 km north of the mouth of Balcombe Creek near Mount Martha and does not extend much inland. It outcrops in the lower part of the valleys of Grices, Dennant and Ballar Creeks in the Mt Eliza area, where it dips gently seawards. Its thickness is variable. On the northern side of Landslip Point Gostin (op. cit.) records it at about 1 m, but at sea level on the southern side of Landslip Point it is at least several metres thick and 1 km north of Sunnyside Beach its thickness was measured at c. 50 m by Gostin (op. cit.).

The *Fyansford Formation* is often a failure surface for landslides in this coastal region. The overlying Baxter Sandstone at Landslip Point has slipped on it as a major landslide still active (Neilson, 1985) and at Daveys Bay nearby, a similar active slide is evident (Dennis, Price & Miller., 1993). Other failures in it have been reported along Ballar Creek, Mt Eliza (Neilson, 1995) and at Fossil Beach, Mornington (Gostin, op. cit.), Mt Martha North (Lane Piper, 2009B), Ansett and Norman Myer properties (Lane Piper 2007A and Golder Associates 2007). Severe erosion of cliffs in the Fyansford Formation along Balcombe Bay has led to the sliding of overlying granular materials from the Baxter Sandstone (Kitson, 1900).

About 0.5 km northwards of the coastal end of Sunnyside Road near Sunnyside Beach, another landslide has been observed with material from the Baxter Sandstone apparently failing on the Fyansford Formation beneath. Wave action is eroding the toes of the landslides at Landslip Point and Daveys Bay and the Fyansford Formation itself, thus helping to maintain movement of these slides.

Care should be exercised in the Port Phillip Bay coastal region where the Fyansford Formation occurs at shallow depth as more slope failures are possible in cliff landscapes.

In the eastern part of the Mornington Peninsula towards Western Port Bay the Sherwood Marl is the equivalent of the Fyansford Formation and is entirely sub-surface with the exception of two restricted outcrops. It is not associated with any slope hazards.

5.8 The Baxter Sandstone (Tertiary: Late Miocene)

The *Baxter Sandstone*, originally defined by Keble (1950), is a terrestrial unit composed of fine to coarse sands, sandy clays, clayey sands, silty clays and some gravelly materials. Variable lateritic weathering has commonly given mottled and variegated red and brown colours and weak to strong cementation. Colours include pale grey, white and yellow. Considerable lateral and vertical variation in material types, colours and cementation are characteristic. Bedding is approximately flat though not prominent and cross-bedding is found.

The *Baxter Sandstone* occurs as a sheet capping much of the landscape and overlies a varied assemblage of rock types. Its surface is undulating to fairly flat. Jenkin (1974) gives its thickness along the coast as about 12 m, increasing to a maximum of about 24 m in places.

Observations indicate that this formation is not a landslide hazard, and that it has failed in slides only through the mechanism of a failure surface of weak materials beneath, chiefly the *Fyansford Formation*, as already described in a number of examples. A major slip in the *Baxter Sandstone*, presumably with this mechanism, is recorded south of Mornington at Balcombe Bay (Kitson, 1900; Keble, op. cit.; Jenkin, 1988). A failure could still occur within the *Baxter Sandstone* on a sufficiently steep slope where it is composed chiefly of clayey materials, though no example of this is known.

The coastal cliffs at the end of Sunnyside Road, about half-way between Mt Eliza and Mornington, have failed in a major slide which, starting 200 m back from the coast as a wide arc, has caused damage to adjacent land and the road itself. Sands – some cemented into sandstone by iron oxide – sandy clays, clays and minor gravels of the Baxter Sandstone have slipped by shear failure on an inclined surface of basaltic clay of the *Older Volcanics* (Gostin, 1966). The basalt, weathered to a high degree, outcrops close to sea-level but is not shown on the 1: 63 360 Cranbourne Geological Survey map (1967).

Along the coast between Frankston and Mount Martha, the *Baxter Sandstone* is in parts susceptible to erosion, undercutting and collapse by wave action. The coastline immediately south of Landslip Point retreated up to 20 m between 1951 and 1990, where wave action has removed the Fyansford Formation at sea-level and failed Baxter Sandstone material at the toe end of a major landslide (Anon., 1993) and at the northern end of Daveys Bay in a similar landslide environment coastal retreat in the same period was about 10 m and some slumping of the cliff face is occurring between Daveys Bay and Pelican Point.

The *Baxter Sandstone*, is a red-brown and pale clayey sand cemented by iron oxide and resistant to erosion, is found on three headlands, viz. the southern end of Canadian Bay, Pelican Point and Davey Point. The first of these is a vertical cliff and the other two are sub-vertical cliffs undercut by wave-cut notches threatening cliff collapse in some future year (Dennis, Price & Miller, 1993). Less cemented materials also in these cliffs give some irregularity to their profiles.

From Canadian Bay to Davey Point the bays and sections of coast away from the headlands are composed predominantly of little ferruginised sandy clays and clayey sands which are easily eroded (Dennis, Price & Miller, 1993). Gostin (1966) made the observation of headlands in well-cemented materials and bays in areas of little cementation for the coast between Davey Point to Grices (Gunyong) Creek and these conditions along the coast with Baxter Sandstone as far as Mount Martha. The underlying *Fyansford Formation*, where it outcrops along the strandline or even slightly below the strandline, has had a significant role in the coastal sculpture.

At Mornington hard ferruginous sandstone is exposed at Red Bluff (Rosengren, 1988), from which boulders and shingle of this rock derived from marine erosion and rock fall cover the adjoining shore platform, Very similar conditions are found nearby at Schnapper Point and Linley (Fishermans) Point (Rosengren, op. cit.; Bird, 1993).

The *Baxter Sandstone* extends eastwards and northwards from the end of the basalt coast in Western Port Bay near Balnarring Beach to Tyabb. It is fronted by Quaternary sandy beaches through Somers to Sandy Point. Some erosion of the beach has occurred at Somers but drifting sand has prograded Sandy Point (Bird, 1993). North of Sandy Point a prograding coast of salt marshes in Quaternary peaty clay and sandy clay with fringing mangroves on a sandy bottom (Jenkin, 1962) reaches to Tooradin.

5.9 Pleistocene Dune Sands

5.9.1 General

Two types of dune sands are found on the Mornington Peninsula (Jenkin, 1974):

Siliceous sands from the Frankston –Cranbourne-Tyabb- Tooradin area

These are sheets and NW-SE trending dunes, occurring northwards of a line reaching SE from Frankston to Western Port and resting on a varied terrain of Baxter Sandstone and older rocks.

They are composed of fine to medium quartz sand, with some surface staining of iron oxide to give commonly a yellow appearance. The dunes display a podsolic soil profile, with pale grey loose sand resting on a weakly cemented dark brown layer with iron oxide and humic material, underlain in turn by reddish yellow clayey sand and finally the yellow parent sand. These are of lesser importance on account of their distribution and will not be discussed further.

Calcareous sands covering the Nepean Peninsula

These are calcareous dune sands, known as dune limestones, aeolianites or calcarenites in cases where they are cemented. These sandy materials will be discussed further below, as they are important in coastal sculpture and on account of their large geographical extent.

5.9.2 Calcareous Sands

The parent materials for this geological unit are quartz in the fine to medium size range, estimated at 25% of the total material by Keble (1950) and 20% by Bird (1993), the remainder being calcium carbonate from shells. They are of wind-blown origin, as shown by the changeable angles of dip and truncation of bedding planes which are typical features of aeolian cross-bedding.

As described by Jenkin (1974), this geological unit is variably cemented by calcium carbonate through solution of the shell component and its later crystallization as a cement, to yield materials ranging from hard concretionary limestone and friable sandy limestone to loose sand. Selective cementation commonly preserves the original bedding. The dominant cemented material is mostly referred to as dune limestone or calcarenite.

The loose sand originates as part of the weathering process, mainly by solution of carbonate by downward percolating water and its deposition at lower levels as calcrete horizons, to leave a blanket of quartz sand over limestone, with varying degrees of induration. Some well-cemented zones have considerable lateral and vertical extent but patterns of cemented zones, loose zones and soils are spatially quite variable. Weathering is also reflected in sub-horizontal soil horizons of red-brown sandy clay visible in some exposures. A noteworthy series of buried soils is found at Diamond Bay, on the Bass Strait coast near Sorrento (Bird, 1993).

The maximum thickness of the calcareous sand or calcarenite sequence on the Nepean Peninsula in the Sorrento area, established by sedimentation and fossil studies of borehole samples, is 84 m (Holdgate, 1976), replacing an earlier estimate of 130 m by Keble (op. cit.). The base of the calcarenite sequence outcrops in the coastal cliffs at Cape Schanck. The Selwyn Fault is responsible for the great thickening of these beds on the down-throw side of the fault along the Nepean Peninsula as found at Sorrento.

South of Rosebud, the Dromana Tunnel of the South Eastern Effluent Outfall passed through mottled grey and brown sandy clay and clayey sand of low cohesion above to finish with yellow to brown fine to medium grained sand having slight or no cohesion in the tunnel crown (Thornton, 1972) at the depth of 11 m. These materials all appear to correlate with the Baxter Sandstone though it is possible that the sand in the tunnel crown might belong to the Pleistocene calcarenite sequence. The materials in the 11 m interval between the tunnel crown and the ground surface are unknown but according to the 1: 63 360 Sorrento Geological Survey map (1965) the Pleistocene calcarenite materials should be found there.

The Nepean Peninsula, from Cape Schanck and Rye to Point Nepean, is an irregular dune landscape, with a substantial inner area of hollows and knolls known as “The Cups” (Keble, op. cit.). The capping of loose dune sand, derived from solution of carbonate from the calcarenite and re-worked by wind action, is irregular in thickness and through it the 1: 63,360 Sorrento Geological Survey map (1965) indicates there is sporadic exposure of calcarenite. In this area there are no streams and water all percolates underground. Planning needs to consider the issues of an irregular landscape in loose sands. The pronounced dune landscape is not found east of the Rosebud-Flinders Road.

Headlands on the coast are found where hard resistant calcrete layers outcrop. The less cemented dune sands are excavated as embayments (Bird, op. cit.).

Along Port Phillip Bay, White Cliffs near Rye, The Sisters together with Point McArthur near Sorrento and Point Franklin at Portsea are examples of headlands in well-cemented calcarenite along a sandy coast (Rosengren, 1988). The last three have hazards of rock falls and collapse through steepness, variable cementation and structural features.

The Bass Strait coast is characterized by high energy wave attack and coastal retreat as shown between Point Nepean and The Divide south-east of Blairgowrie by hard calcarenite features such as wide shore platforms, small embayments, rock stacks and other detached masses of calcarenite, the off-shore rock arch London Bridge, steep cliffs up to 50m high and caves (Keble, op. cit.). These are followed to the south-east by sandy beaches backed by Holocene dunes until 3 km north of Cape Schanck where the Selwyn Fault is crossed. Here the dark grey basalt of the Older Volcanics rises above the sea in cliffs capped by the Pleistocene calcarenite. The cliffs on this coast have hazards of rock fall, collapse and incipient failure which have not been evaluated. The variability of cementation, slopes and surface features are also factors relevant to planning.

A study at Boags Rocks, on the coast 8 km NW from Cape Schanck, found cliffs and wave cut platforms in calcarenite backed by coastal dune sands (Coffey, 1998). Rock samples collected were described as “fine to medium grained, massive calcarenite”, with colours varying from grey to yellow-grey, yellow-brown, yellow, green-brown and green-yellow-brown. Point Load

Strengths (I_{s50}) ranged from 0.10 to 4.38 MPa, i.e. very low to very high, with five samples in the high range, four samples in the low - very low range, two samples in the very high range and one sample in the medium range. Dune bedding with laminae dipping at 0-30 degrees were recorded with abrupt terminations of dip, bedding thickness ranging up to 100 mm and undefined vertical to sub-vertical discontinuities spaced at about 1 m intervals. The degree of weathering was described as almost entirely within the “High” to ‘Medium” range, but these categories were not defined for calcarenite. The information given does not allow a clear picture to be drawn of the rock mass.

5.9.3 Holocene Deposits

Some Holocene features associated with coastal features have already been mentioned and others are mentioned below. Few slope problems are envisaged, unless over steepened by construction works.

An extensive body of loose mobile calcareous sands in the form of dunes reaching more than 30 m in elevation is found along the Bass Strait coast of the Nepean Peninsula from Rowley Rocks about 4 km northwards of Cape Schanck to a small headland SE of Blairgowrie named The Divide. They have originated through wave and wind action on sand produced by solution of the calcareous cement in calcarenites. Partly fixed by vegetation, wind action and blow-outs from these dunes have distributed some loose sand across the Nepean Peninsula. Construction in these sands would need to consider their mobility, variable density though loose packing of grains and steep slopes in parts.

Bird (1993) has noted low sand beach ridges behind the strandline between Dromana and Blairgowrie. Near Point Nepean on the Port Phillip Bay coast, growth of a series of parallel sandy ridges about 500 m beyond a former cliffed shoreline cut in Pleistocene calcarenite has extended the coastline to create Observation Point. The Point is now undergoing minor erosion on its west side and growth on its east through the current growth of new low ridges (Rosengren, 1988). The distinctive origin of these landforms should be heeded in construction.

Swamp deposits, in some of which such as the Tootgarook Swamp peaty soils have been identified, can be expected to have difficulties in foundation conditions. The alluvium associated with streams will show considerable variability across the Mornington Peninsula because it is derived from a range of different parent materials, which is a cautionary note for planning and construction.

5.10 Summary of Literature Study

Ordovician sedimentary rocks

The probability of slope failures in these rocks has been identified and should be studied. Again aerial photographs have been examined and further evaluation as areas are developed is recommended.

Granitic rocks (Devonian)

Deep seated failure in slopes within the granitic rocks has not been recognized and aerial photographs have been examined for any evidence of possible slope instability. Highly jointed and prone to boulder failures in quarry excavations.

Coastal exposures of granitic rocks were examined using aerial photographs. Investigations along the coastal cliffs have demonstrated the relative stability of these cliffs but the occurrence of shallow failures and occasional deeper failures cannot be precluded.

Basaltic materials of the Older Volcanics (Tertiary)

Slope failures in these materials on hillsides are fairly widespread. It is the major source of slope instability on the Mornington Peninsula. Aerial photographs have delineated a number of these failures and investigations have confirmed these assessments.

Fyansford Formation (Balcombe Clay) (Tertiary)

The stability of this formation along the Port Phillip Bay coast and its relationship with slope failure of overlying geological formations is a major issue along the Port Phillip Bay coast for developments near the coast.

Baxter Sandstone (Tertiary)

This formation is not regarded as a slope hazard. Aerial photographs tend to confirm this conclusion, apart from along the coast where it is undermined by wave action. Generally failures of the Baxter Sandstone occur only on contiguous failure surfaces in underlying geological units.

Calcareous sands and calcarenite (Pleistocene)

The stability of coastal cliffs in these materials needs assessment on the grounds of steepness, profiles, variable cementation and zones or surfaces of weakness. The extent of this assessment would depend on how closely land use questions impinge on the coastal cliffs. Inland there are issues of surficial loose sands with irregular topography, which may call for engineering appraisal.

Coastal dunes, beach ridges, swamp and alluvial deposits (Holocene)

The dunes are mobile to a considerable degree and pose problems for construction if locally steepened. The other materials are without slope problems but many are variable in their characteristics and have other engineering issues as some are of low strength.

6 REVIEW OF THE CONSULTANTS' REPORTS

As part of this assessment a number of consultants' reports have been reviewed and summarised. The review was conducted in order to aid in the calibration of the susceptibility model and also to produce a database of the consultants' reports for use when assessing individual properties.

At the time of the preparation of this report a total of 158 consultants' reports had been reviewed. However, the purpose of the database is to provide an ongoing resource of materials that can be updated by Council as investigations are conducted. It is likely that there are already additional reports available to Council which can be added to the database.

Details of the review are provided in Appendix C.

7 PREVIOUS LANDSLIDE SUSCEPTIBILTY STUDIES

There have been several studies of landslide susceptibility previously conducted for areas within the Mornington Peninsula Shire. These are:

- Ballar Creek, Mt Eliza – Coffey (1999)
- Tanti Creek, Mornington – Lane Piper (2010B)
- Flinders Township – Lane Piper (2008A)
- Hearn Creek, Mt Martha – Piper & Associates (1999)

The recommendations of the first three studies have already been incorporated into Erosion Management Overlays (EMO) by the Mornington Peninsula Shire and the recommendations of those studies provide guidance for the development of properties with the study areas.

The locations of the studies and the EMO recommended by the studies are shown in the following figures. For each study area red indicates high landslide susceptibility, yellow indicates medium landslide susceptibility and green indicates low landslide susceptibility where shown.

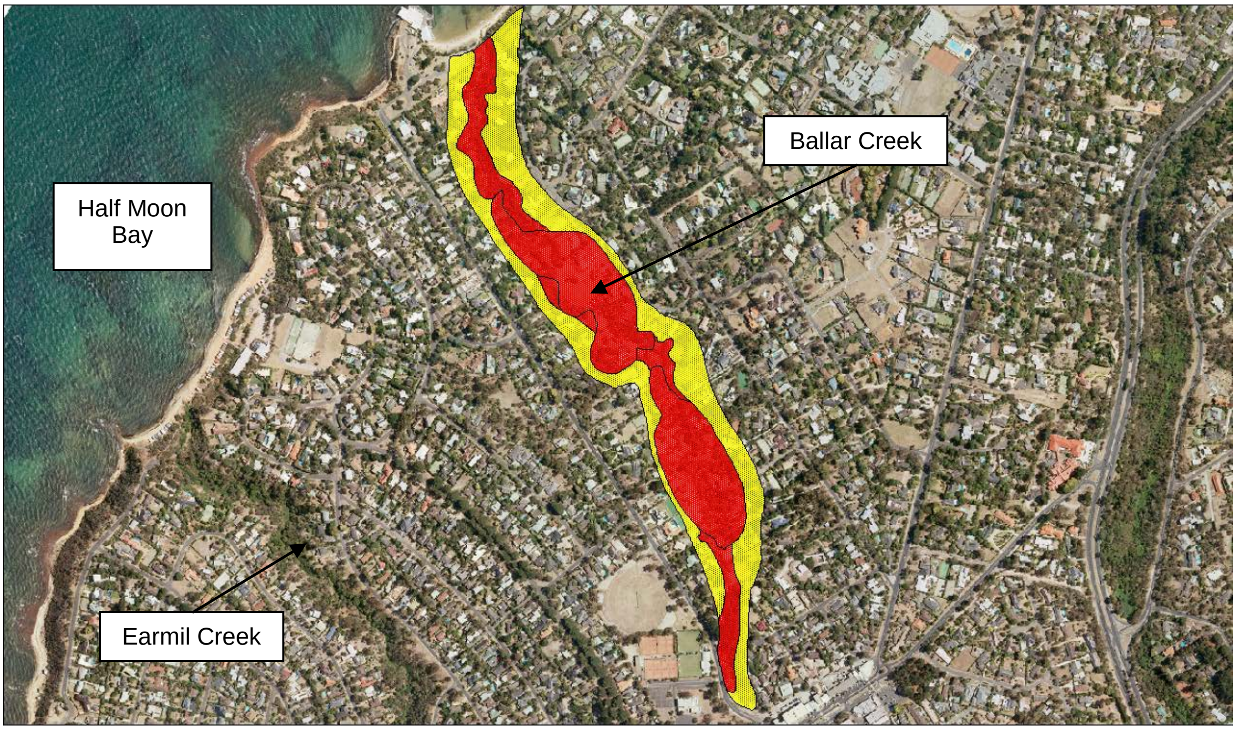


Figure 7-1: Ballar Creek Landslide Susceptibility Zones

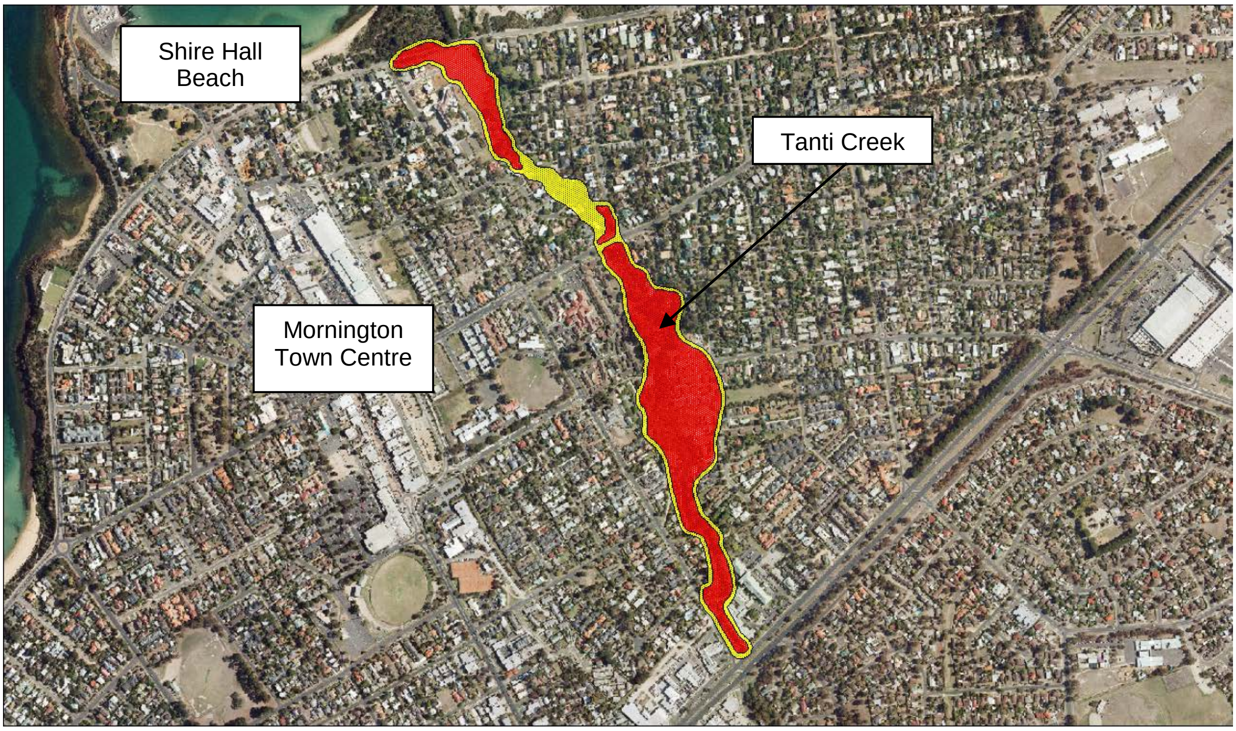


Figure 7-2: Tanti Creek Landslide Susceptibility Zones

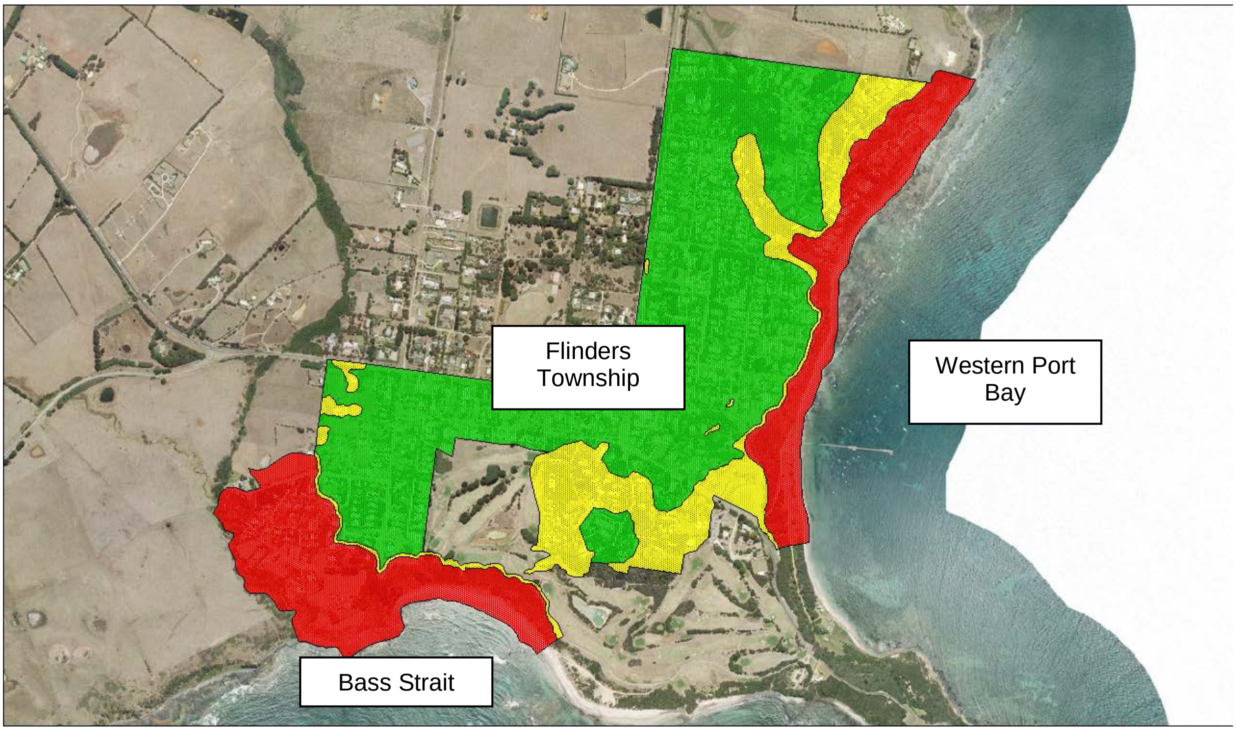


Figure 7-3: Flinders Township Susceptibility Zones

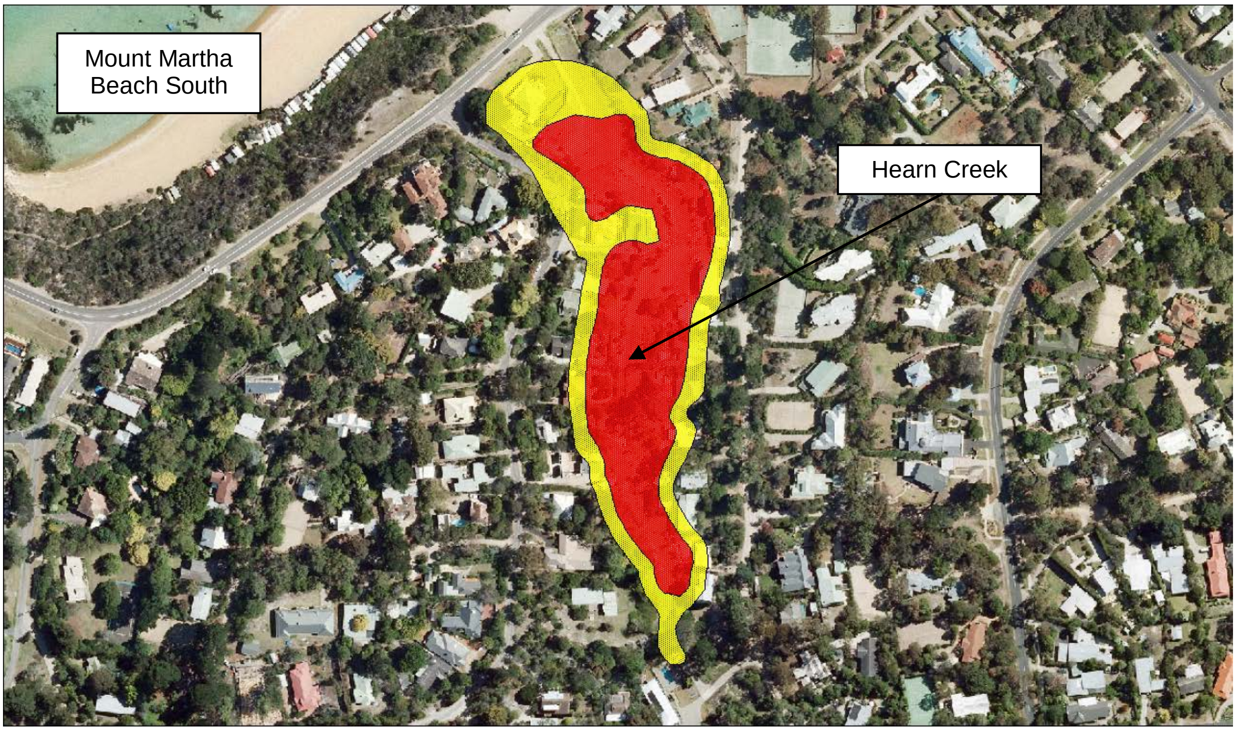


Figure 7-4: Hearn Creek Susceptibility Zones

In order to provide consistency between these previous studies and any future EMO's that the Shire may adopt, the landslide susceptibility boundaries defined in those studies have been adopted in the current study. Where there is a discrepancy between a previous study and the results of the current study, the recommendations of the previous study overrule.

These detailed studies have also been used to verify the accuracy of the GIS model.

8 AERIAL PHOTOGRAPHIC EXAMINATION

8.1 General

The study of aerial photography is to identify slope failures as far as possible by stereographic study of recent colour aerial photographs. The Greater Melbourne 1998 Series of photographs, Runs 34 to 49 and the additional Run 52 was initially used for Stage 1 of the assessment. The location of each photograph is given on maps of run lines accompanying the photographs supplied. Some 210 photographs were examined.

For Stage 2 of the assessment, digital versions of the Department of Sustainability and Environment series, *CIP 2005-06 Mornington Project*, were reviewed to confirm the slope failures previously identified and also to identify further areas of failure.

It was not possible to conclusively identify slope failures on the aerial photographs in many cases. Slope failures are generally marked by unexpected changes in slope profiles. Changes in slope profiles can however also be caused by the presence of rocks of different degrees of hardness, variable depths of rock weathering, geological structures and differences in the vigour of the processes of erosion which have shaped a landscape. The shapes of different types of slope failures are characteristic but they can be like some other geomorphological features and can be difficult to identify from the study of aerial photographs alone. Field examination is necessary to ascertain identification of slope failures in many cases. Even with experience, one cannot be sure of seeing and recognizing every possible slope failure on aerial photographs: in particular, small failures, those with little topographic expression and others beneath a cover of trees can be difficult to see.

8.2 Types of Slope Failures

The classification of Cruden and Varnes (1996) is used in the present study. Reference should be made to this work for detailed descriptions of failure categories.

The following types of slope failures have been recognized:

- Falls – both rock falls and earth falls,
- Slides – probably both rotational (concave curved rupture plane) and translational (sub-planar rupture surface),
- Flows – earth and debris flows, which develop from rotational earth and rock slides, possible isolated earth flows, sand flows developed on dry dunes and beach berms assisted by wave sharpening and
- Aeolian sand features – blowouts and other mobile sand features, which can lead to collapses. (The aeolian sand features are not covered by the classification of Cruden and Varnes.)

9 DIGITIZATION OF THE DATA

The various data sources have been processed to produce digital data in readiness for establishing a slope stability model. These data sets are as follows:

- Geology Zones
- Identified Slope Failures
- Previous Consultants Reports
- Landslide Susceptibility Studies
- Digital Terrain Model
- Water Table & Rainfall

A discussion of the digitization of the data for each of the sets is provided in the following sections.

9.1 Geology Zones

As discussed in Section 4, the geology of the Mornington Peninsula is complex. The Shire is covered by three 1 inch to 1 mile (1:63,360) geological maps as follows:

- Western Port
- Sorrento
- Cranbourne

These maps were produced in the 1960's. The boundaries for the main geologies identified in Section 4 have been digitised from the scanned maps with each geology given an identifying colour. In order to simplify the analysis, geologies that have common attributes with regard to slope stability have been combined. The different geologies are as follows:

1. Siltstone (Light Blue)
2. Granitic Soils (Red)
3. Older Volcanics (Orange)

4. Balcombe Clays (Dark Brown)
5. Baxter Sandstone (Yellow)
6. Pleistocene Sands (Light Green)
7. Quaternary Alluvium (Dark Green)

The spatial accuracy of the geological boundaries is unknown but it would be reasonable to conclude that they would be no better than 100m.

A copy of the digitized geological map is provided in Appendix A.

9.2 Identified Slope Failures

The study of aerial photography discussed in Section 8 identified numerous possible to certain landslides across the Mornington Peninsula. While some of the identified possible landslide may not in fact be landslides, they have the appearance of landslides on the aerial photography. Therefore, it was considered appropriate that all of the possible landslides be included in the study. An individual field and intrusive assessment of the sites may identify that some of the 'potential landslides' are in fact not landslides.

A copy of the digitized map of the identified slope failures is provided in Appendix B.

9.3 Previous Consultants Reports

The results of the previous consultants' reports have been summarised into a geo-referenced database. The location of the site for each report can be determined by viewing the map view of this geo-referenced database.

Selecting the icon for the report in this map will open a summary of the report. This summary also includes a hyperlink to the full report.

A copy of the map showing the consultants reports that have been included in the database is shown in Appendix C.

9.4 Landslide Susceptibility Studies

The locations of the previous landslide susceptibility studies discussed in Section 7 form one layer of input for the susceptibility model. The zones within these previous study areas will overrule any susceptibility analysis.

A copy of the map showing the previous susceptibility areas is shown in Appendix D.

9.5 Digital Terrain Model

When this study was originally commissioned there were several sources of Digital Terrain Model (DTM) data available for the Mornington Peninsula.

The most comprehensive data at the time of commencement of the study was based on aerial photogrammetry (*CIP 2005-06*). However, this data only covered approximately 80% of the Shire and it was planned to incorporate any new data into the study as it became available. As this data was the most readily available at the time of commencement of the project it was used for initial calibration of the susceptibility models and for development of the analysis code. Unfortunately, it was determined that the final areas of photogrammetric data would not be available in a timely manner and as such alternative data sources were investigated. Also, while the photogrammetry data was fairly comprehensive it tended to 'average out' the slope gradients determined and therefore small sudden changes in gradient such as small cliffs, cut slopes and retaining walls were sometimes not clearly identified in the data.

Another source of DTM data that was available was LIDAR (LIght Detection And Ranging) data. While DTM's generated from this form of data are considered more accurate than photogrammetric data, the LIDAR coverage at the time of commencement (CIP 2006-7) of the project was only for approximately 60% of the Shire. Hence, the reason it was not originally selected for use in the analysis.

Over the following three years, further LIDAR data became available until in mid 2010 when data was available which covered the full extent of the Mornington Peninsula Shire.

The first step of adopting the LIDAR data for use in the susceptibility model was to determine its suitability for use and consistency between the different data sets. A comparison was made between the different sets where there were overlaps in data. While the data was identified as having a vertical accuracy of +/- 0.1m, a significant portion of the common data points had vertical differences of in excess of 0.2m which should in theory be the maximum vertical difference between points. Some of the points were observed to have vertical differences of greater than 2.0m for the same grid locations.

It was observed that while a few of the discrepancies occurred outside treed areas, most of the discrepancies occurred in heavily vegetated areas. Therefore, it appeared that in these treed areas there were false data readings due to the trees. In order to reduce the discrepancies, an algorithm was developed to adopt the lower reading where two sets of LIDAR data were available for a common point. Also, the data was analysed for single spikes surrounded by lower points and these were also reduced in elevation. Using these methods, the multiple different LIDAR data sets which have a 1m grid of data points, approximately 1 billion data points, were reduced to a single set of LIDAR data points with a 2m grid of data points, approximately 250 million data points.

The new LIDAR DTM was then used to produce a 0.5m contours for the entire Shire as well as slope gradient and aspect values for each point on the 2m grid across the shire.

A plan showing the 10m contours for the Shire is included in Appendix E.

9.6 Water Table & Rainfall

The water table data from the State groundwater database was related to the depth to the ground water resource and not necessarily the depth to the first occurrence of the groundwater. Furthermore the data was widely spaced. Insufficient groundwater data did not allow it to be related to the terrain topography and was misleading.

There were few rainfall data recording points across the Shire and while it is recognised that south facing slopes will have a greater rainfall and greater rainfall infiltration, there was insufficient data to be able to quantify this.

Consequently it was decided not to include the water table and rainfall data in the GIS model.

10 ESTABLISHMENT OF A SUSCEPTIBILITY PREDICTION MODEL

10.1 Adopted Characteristic Maps

As discussed in Section 8, digital characteristic maps have been created that identify the geology, known slope failures, existing susceptibility overlays, slope, aspect, groundwater depth, rainfall and locations of geotechnical reports.

The susceptibility model has been created based on these source data models. The accuracy of each of the source data models is highly dependent on the accuracy of the original data. The following comments are made with regard to the accuracy or suitability of the source data:

- **The slope and aspects** are based on LIDAR data on a grid at 2m centres and so can be considered to have a good level of accuracy. However, a review of the LIDAR detected anomalies in the area of the trees or buildings. These anomalies have been addressed by the geospatial surveyor and analysis algorithms.

  The geology model is based on published geological maps with a scale of 1:63,360. Although the geology maps are considered to be accurate, identification of the geology to a 2m accuracy is not possible. Instead, the geology is considered accurate for the local area. However, the accuracy is considered sufficient for the classification of landslide susceptibility. A more accurate delineation of the geology would be required when assessing the stability of individual properties as part of a detailed investigation.
- **The groundwater depth** model is based on the results of monitoring wells and piezometers. Although the depths are likely to be accurate in the vicinity of the well, there are significant areas where there is no groundwater information and interpolation was required to produce the data. For this reason, the groundwater results can generally not be considered accurate on a local scale and therefore the effects of groundwater on landslide susceptibility were not considered. Nonetheless it is recognised that the groundwater including perched rainfall, can have a significant effect on the slope stability
- **The rainfall data** model is based on the results from weather stations. However, due to the limited number of weather stations across the peninsula, the data can only be considered to be regionally accurate. As with the groundwater, localised variations in rainfall could have a significant effect on susceptibility that are not correctly reflected in the rainfall data. Therefore, the effects of rainfall were also not considered.
- **The aspect**. Southerly facing slopes are more susceptible to slope failures as they are generally wetter than northerly facing slopes, but there was insufficient data to be able to include this affect in the model. For the Balcombe clays, the down warp on these clays has reduced the shear strength in the direction of the dip. These clays are known to stand at much steeper slopes when excavated at angles away from the dip direction and an allowance for the dip direction was included in the area of the Balcombe clays.

10.2 Susceptibility Analysis Procedure

The susceptibility to landslides for each 8 x 8m square section for the entire Peninsula was determined.

The susceptibility analysis involves analysing the available data on an 8m grid over the whole of the Mornington Peninsula Shire. For each point on the grid, the following general methodology is adopted:

1. Determine whether the point is within the study area of the Mornington Peninsula Shire, if not, ignore;
2. Determine whether the point is within an existing EMO. If so, adopt the susceptibility value from the EMO;
3. Determine whether the point is within a known probable or possible landslide, if so, adopt a high susceptibility value;
4. Determine the geology of the point;
5. Determine the maximum slope gradient of all LIDAR 2m grid points within a 6m radius. The 6m radius was selected to ensure that any sudden changes in slope between each 8m analysis point were picked up. This ensures that the most conservative, i.e. steepest, slope in the vicinity of the point is used for the analysis and the impacts of nearby features such as cliffs, cuts and retaining walls were not missed.;
6. Determine the average slope aspect of all LIDAR grid points within a 6m radius. This establishes the general orientation of the slope in the local area and allows directional bias to be used in the analysis;
7. Calculate the susceptibility value based on the geology, slope gradient and aspect.

In order to appropriately quantify the landslide susceptibility of a site, compare the site to other sites and place development criteria on a site for a particular level of susceptibility, a classification system has been developed to define the landslide susceptibility. This involves classifying areas in zones of low, medium and high landslide susceptibility.

As indicated above, the primary inputs in determining the susceptibility are the geology, slope gradient and aspect. Based on inspection of various landslide sites in the peninsula and review of previous investigations, it has been established that generally any two locations that have the same slope gradient, aspect and geology will have the same susceptibility value. Considering this, it is appropriate that for each particular geology, a range of susceptibility values will apply to a range of slopes.

In order to be able to compare the susceptibility of the different geologies, an **arbitrary weighting** system has been developed for defining the susceptibility of a particular location. This system defines the susceptibility weighting to have a value of between 0 and 30 with a value of 0 indicating the site is unlikely to ever have slope instability without significant modifications to the site and a value of 30 indicating that the site has either already had slope instability issues or is very likely to be subjected to have slope instability issues in the future based on other failures in a similar geology and slope.

The landslide susceptibility classifications of low, medium and high susceptibility are then defined susceptibility weightings as follows:

- Low Susceptibility (Green): 0 – 10
- Medium Susceptibility (Yellow): >10 – 20
- High Susceptibility (Red): >20 - 30

The boundary between low and medium susceptibility has been defined as the point beyond which creep movement is likely to occur, but not necessarily a slope failure. Slopes that have a steeper gradient will have a susceptibility weighting of greater than 10 for a particular geology

The boundary between medium and high susceptibility have been defined as the point beyond which slope failures have either previously occurred or are considered possible. Slopes that have a steeper gradient will have a susceptibility weighting of greater than 20 for a particular geology.

The landslide susceptibility weighting values are then used by interpolation between each data point to define the locations of the boundaries between the different landslide susceptibility zones.

As the different geologies have different gradients values where creep and landslides will begin to occur, the gradient which defines the low/medium and medium/high boundaries will vary for a particular geology.

The following two sections identify how the effects of slope gradient and aspect on the susceptibility were determined. The subsequent sections discuss the verification of the predicted models for each geology against known values from previous geotechnical investigations and studies.

10.3 Effect of Slope on Susceptibility

In order for the susceptibility of a slope to be determined, boundaries need to be established which define the extent of that susceptibility. As previously indicated, the susceptibility of a particular point can be defined as being 'high', 'medium' or 'low'. The following guidelines were used to establish the susceptibility criteria for each geology.

High Susceptibility Zone – A high susceptibility zone is considered as an area where significant landslides are possible. This may be due to the presence of known landslides or previous landslide activity or unaffected slopes that have a similar geology to known landslides but have a similar or steeper gradient than the landslide. Landslides identified from previous studies, and aerial photography are included in this zone

Medium Susceptibility Zone – A medium susceptibility zone is considered as an area where significant landslides are considered unlikely, except in unfavourable circumstances, but where creep movement or surficial shallow slope failure is possible.

Low Susceptibility Zone – A low susceptibility zone is considered to be essentially outside the influence of landslide susceptibility and will only be susceptible to landslides if there is significant man made activity.

It is important to understand that these areas relate to landslides and does not consider erosion or debris flow. Erosion can be a function of other factors such as rate of water flow, the concentration of any flow over the slope, the geology, the erodability or dispersivity of a particular soil and the vegetation cover. It does not consider the impacts or issues relating to debris flow from a landslide as the extent and height of debris flow depends on a number of factors such as the volume of the landslip, the slope of the landside and slope below the landside, the type and depth of the landslip, the soil type, ground saturation, groundwater source and other factors.

10.4 Methodology to Determine Boundaries of Landslide Susceptibility

For each of the geologies it was necessary to determine the range of slope angles for each susceptibility zone and the boundaries between the zones. The critical issue in producing a susceptibility zonation plan is to determine the boundaries between areas of susceptibility. The following sections discuss the methodologies for determine the boundaries between the different susceptibility zones.

10.4.1 High/medium Landslide Susceptibility

The **high/medium landslide susceptibility** boundary is the boundary between where significant landslides are considered possible and unlikely. The following methodology was used to establish the high/medium boundary for each geology:

1. Identify known landslides within the particular geology. These have been previously identified from aerial photography and earlier reports.
2. Use the LIDAR data to identify the headscarp of the landslide as the location on the upslope side of the landslide where there is a significant change in slope. In older landslides, the headscarp may be considerably rounded with creep and erosion.
3. Use the LIDAR data to identify the slope directly up-slope and down-slope of the headscarp
4. Repeat for multiple locations along the headscarp of the landslide
5. Repeat for multiple landslides where there is data available
6. The data for up-slope and down-slope of the scarp is then plotted on a chart of slope frequency vs. slope with up-slope and down-slope plotted independently with a minimum of 50 data points. A polynomial curve is then fitted to the data for both up-slope and down-slope. The intersection of the up-slope and down-slope curves is then set as the boundary between high and medium landslide susceptibility. The reasoning behind this statistical methodology is discussed in Section 10.4.3.

10.4.2 Medium/low Landslide Susceptibility

The **medium/low landslide susceptibility boundary** is the boundary between where creep movement can occur and where there is expected to be no influence from the landslide. The following methodology was used to establish the medium/low boundary for each geology:

1. Identify areas of known creep movement within the particular geology
2. If no such information is available, identify areas where the influence of regional slope is taken over by the influence of local slope due to features such as cliffs and creeks
3. Use the LIDAR data to identify the change in slope from the regional to local slope
4. Use the LIDAR data to identify the slope directly upslope and downslope of this change in slope
5. Repeat for multiple locations
6. The data for up-slope and down-slope of the break in slope is then plotted on a chart of slope frequency vs. slope with up-slope and down-slope plotted independently with a minimum of 50 data points. A polynomial curve is then fitted to the data for both up-slope and down-slope. The intersection of the up-slope and down-slope curves is then set as the boundary between medium and low landslide susceptibility.

10.4.3 Statistical Methodology

The intersection of the landslip susceptibility curves was selected as the appropriate slope for interface of the slope susceptibility boundary. This point was selected as it allows the confidence of the data available to determine the boundary location. When the distribution of slopes is narrow i.e. with high confidence, the intersection or selected slope will move towards the centre of the distribution, while if there is a broad range of slopes, the intersection will move away.

This means for the situation where there is a broad range of slopes downslope of a head scarp but a narrow range of slopes up slope of the headscarp, the intersection of the two curves will be moved towards the up slope curve and the model will adopt a less steep slope. Where the distribution up slope and down slope of the head scarp is similar, the model will adopt a value close to the median of the two distributions.

The distribution of slopes for the low/medium susceptibility interface will be greater than for the medium/high susceptibility interface as the former interface is less clearly defined.

The methodology of determining the maximum slope within a 6m radius of any particular slope location will result in a bias of the scarp location to a distance of up to 6m upslope from the scarp location.

A trial susceptibility analysis was then run over the areas of the identified landslides to verify that the adopted susceptibility values provide consistent results.

The individual methods adopted for each geology are discussed in Sections 9.6 to 9.12.

10.4.4 Allowance for Data Variability

While the high accuracy of LIDAR data is very useful for a study of this nature, the high accuracy can result in very small variations being identified as slopes with a significant gradient. For example, a block of land with an overall fall of less than 1m from front to back may have numerous small undulations due to landscaping work or natural processes. A small mound or undulation that is only 0.3m high over a length of 2m would be identified by the LIDAR data as having a slope of 15% while the actual slope across the property is approximately 3%. These localised variations could result in predictions of slope instability but are minor and the overall site has only a gentle slope

The effects of this variation are not considered to have a significant impact on the analysis for moderate to steeper slopes as the variations would have a proportionally smaller effect on the calculated slope. However, for the relatively flat sites, the variations could result in a site being falsely reported as having a medium or even high susceptibility rating. In order, to overcome this problem, an algorithm was developed that identified whether there was a vertical elevation variation of less than 1.1m over the analysed area of 6m radius (i.e. the maximum fall must be less than 10%). Any areas that were identified as having a vertical elevation variation of less than 1.1m were automatically defined as being of low landslide susceptibility.

However, it is also important that the impacts of cliff faces with near flat slopes behind the cliff face are not ignored. The ground surface behind a near vertical cliff face may still be susceptible to a slope failure. This is overcome by adopting the maximum slope within a 6m radius of any point assessed.

As the analysis is conducted on an 8m grid but the data is based on a 2m resolution, it is possible that features such as cliffs and cuts with a width of less of less than 8m could be missed. However, by checking for the maximum slope of every 2m grid point within 6m of the main 8m analysis point it can be ensured that all features are picked up by the analysis.

10.5 Effect of Aspect on Susceptibility

Once the susceptibility of a slope has been determined based in the slope angle, it can then be modified by a factor to allow for the aspect. This can help to allow for dominant weather or pre-existing slip planes.

As it is generally accepted that south facing slopes are more susceptible to landslides than north facing slopes due to the effects of weather, the values in the following table were assumed for the modification factor.

Table 10-1: Modification Factors for Slope Aspect

Aspect	Factor
N	0.98
NW/NE	0.99
E/W	1
SW/SE	1.01
S	1.02

Generally the effects of slope aspect on the susceptibility have been considered minor. However, for the Balcombe clays where slopes of a particular direction have been observed to be greatly influenced by a pre-existing slip plane, the effect of aspect on the stability of a slope has been shown to be significantly higher. This is discussed in more detail later in the section on Balcombe clays.

10.6 Older Volcanics

10.6.1 Background Data

Numerous geotechnical investigations and studies of sites within the Tertiary Older Volcanics geology have identified issues with landslides including the following:

- Rosebud-Flinders Road, Piper & Associates – PA(1993)
- Shoreham, Douglas Partners – DP(2000)
- Flinders Foreshore, Lane Piper – LP(2008A)
- Somers, Lane Piper – LP(2010C)

The locations of these landslides are shown on the aerial photograph in the following figure.

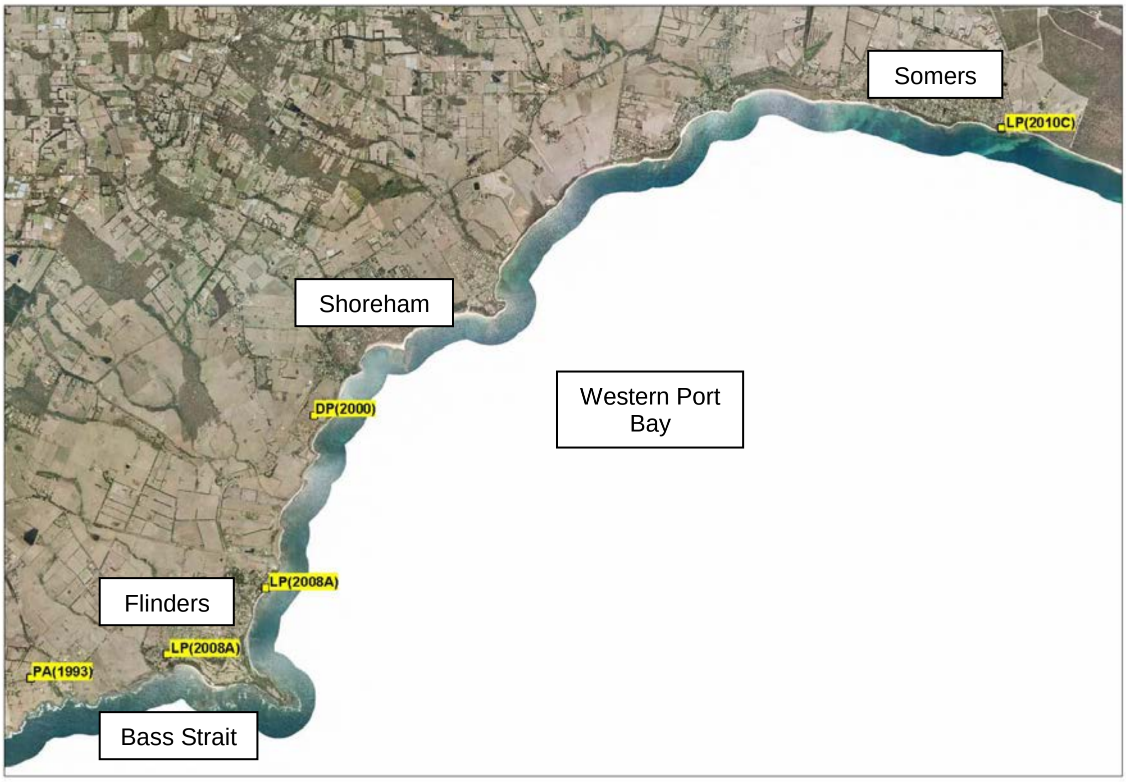


Figure 10-1: Sites used for Older Volcanics Verification

10.6.2 Predictive Model

The predictive model for the landslide susceptibility of the Tertiary Older Volcanics geology was based on landslides identified in the Lane Piper report (2008A).

The location of the landslides has been identified in the 2008A report. The more accurate LIDAR data, which was not available at the time of the previous study, was used to refine the location of the landslides scarps.

The methodology outlined in Section 9.3 was then used to identify the boundaries for the high/medium and medium/low susceptibility boundaries.

For the high to medium slope susceptibility boundary, an analysis of the data indicated that the maximum slopes immediately up slope of the scarp varied between 5% and 40% while the maximum slopes immediately down slope of the scarp varied between 26% and 115%. A total of 494 points were included in the assessment. The intersection between the up-slope and down-slope curves was at 32% so this value was adopted as the high/medium boundary. The following figure shows the distribution of slopes that fell between the up slope and down slope side of the scarps.

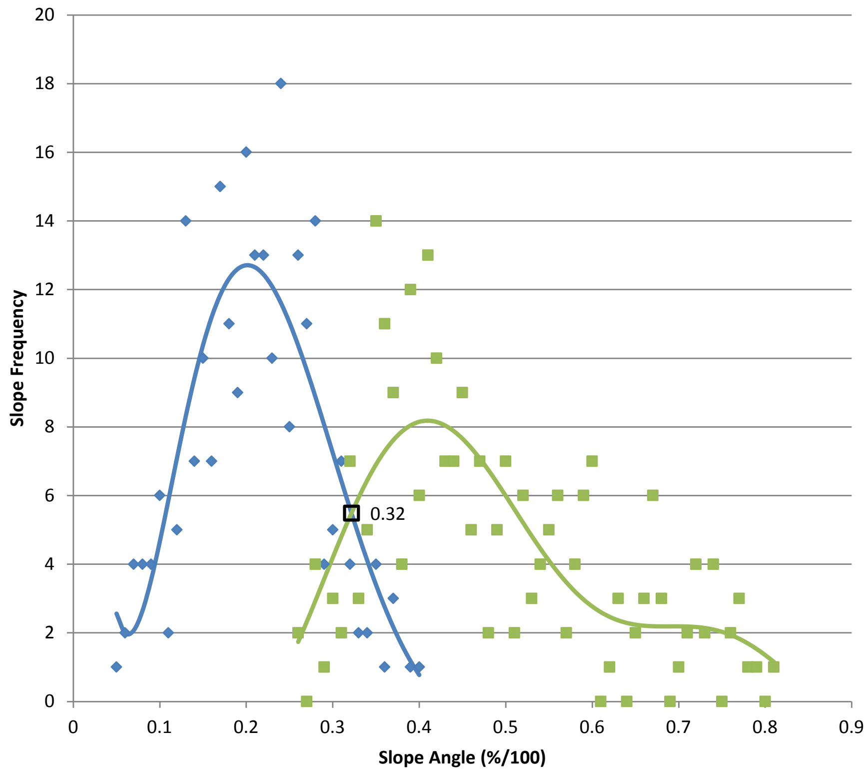


Figure 10-2: Older Volcanics High/Medium Slope Distribution

For the medium to low slope susceptibility boundary, the potential creep zone in the Flinders area was identified as a distinct change in grade from the consistent slopes of the main township area to a gradual fall towards the cliffs and creeks. The identified zone was consistent with the areas where creep has been observed in the previous investigation.

An analysis of the data indicated that the slopes immediately up slope of the start of the creep zone varied between 3% and 15% while the slopes immediately down slope of the start of the creep zone varied between 11% and 50%. A total of 95 points were included in the assessment. The intersection between the up-slope and down-slope curves was at 14% so this value was adopted as the medium/low boundary. The following figure shows the distribution of slopes that fell between the up slope and down slope side of the creep zone boundary.

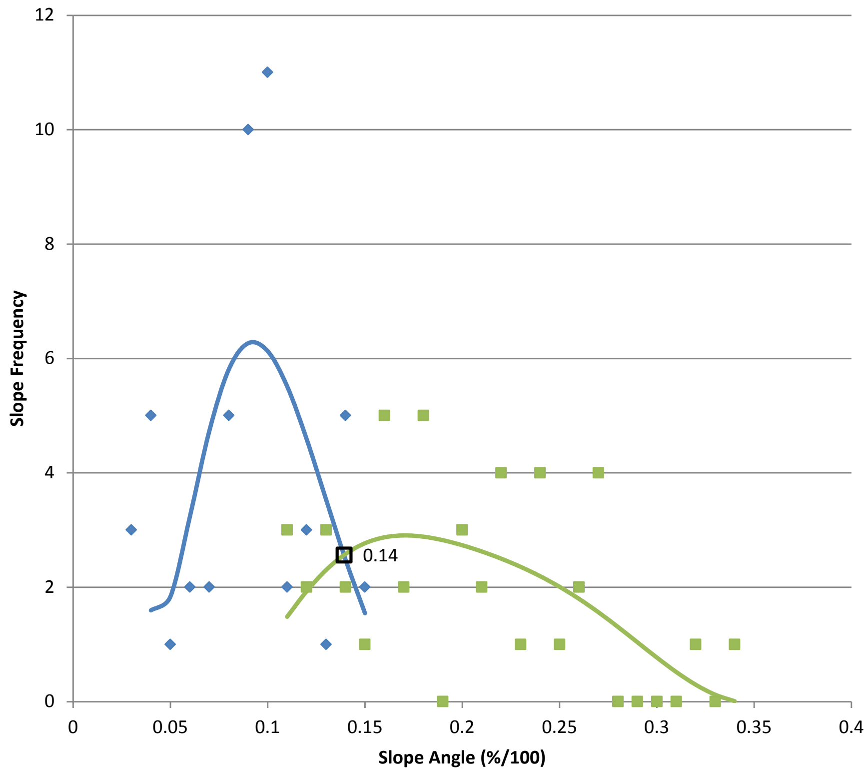


Figure 10-3: Older Volcanics Medium/Low Slope Distribution

The distribution of slopes is far more variable indicating that there are a number of other factors that are influencing the slopes such as groundwater, rainfall, vegetation and underlying rock.

10.6.3 Model Validation for the Older Volcanics

Once the predictive model was established, the model was verified against the landslides identified in PA(1993), DP(2000), LP(2008A), LP(2010C).

Flinders Township South-West

LP(2008A) identified significant landslides along the foreshore and also along the creek banks of Double Creek in the south-west of the Flinders Township. The landslides identified in the report were used to verify the predictive model.

The results of the verification are shown in Figure 9-4 and are discussed below. The boundary of the high susceptibility zone determined from aerial photographs and visual inspections in LP(2008A) is shown as a solid red line while the results of the predictive model are shown as a grid of coloured squares with the red squares representing the predicted locations of high susceptibility.

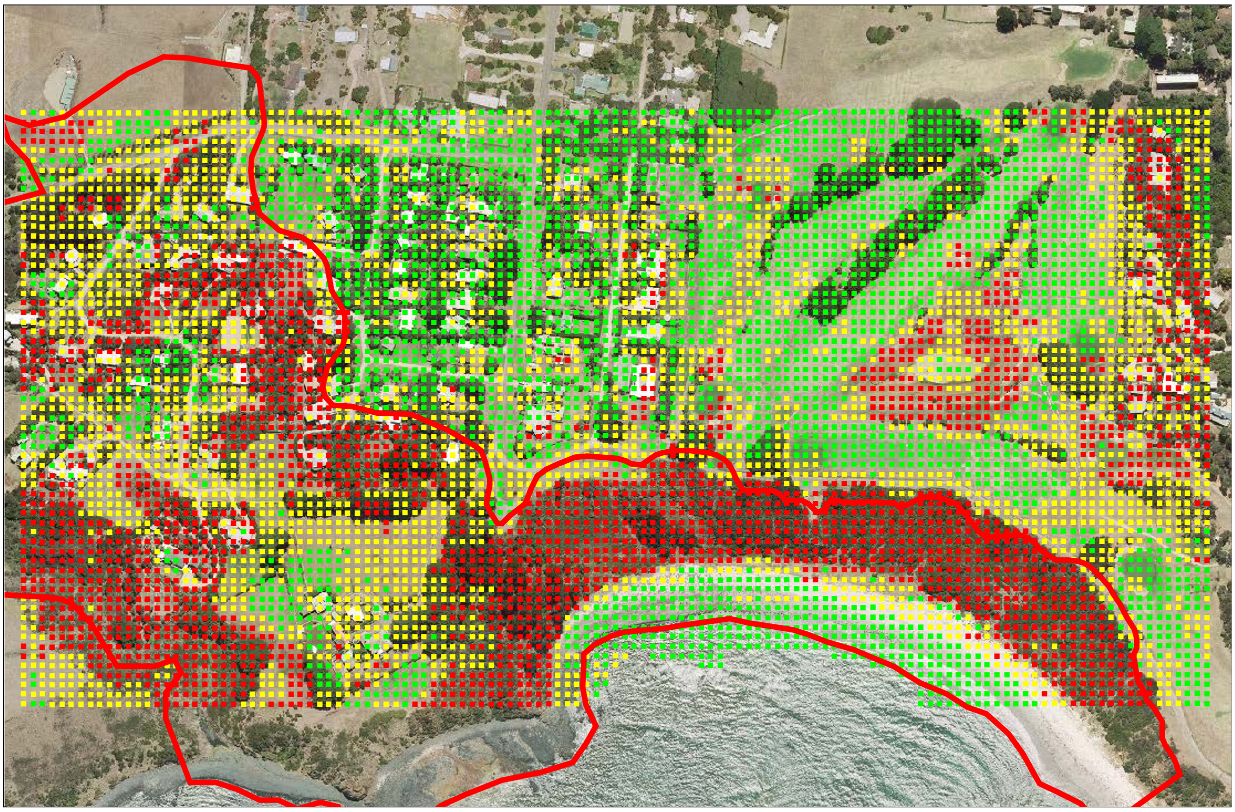


Figure 10-4: Flinders South-West - LP(2008A-1)

The model showed a good correlation with the boundaries identified in LP(2008A) for the south-west of the Flinders township as can be seen above. Differences between the field observations and the model within the red zone are as a result of accumulation zones of landslides which cannot be predicted by the GIS model. The model also highlights a large dam to the north of the cliffs in the east of the plan. This dam was outside the previous study area.

Flinders Township East

LP(2008A) as well as numerous other reports have identified the landslides along the foreshore in the vicinity of Spindrift Avenue in the east of the Flinders township. These landslides were used to verify the model for the Older Volcanics geology.

The results of the verification are shown in Figure 9-5 and are discussed below. The boundary of the high and medium susceptibility zones determined from aerial photographs and visual inspections in LP(2008A) are shown as a solid red and yellow lines while the results of the predictive model are shown as a grid of coloured squares with the red squares representing the predicted locations of high susceptibility and yellow squares representing the predicted locations of medium susceptibility.

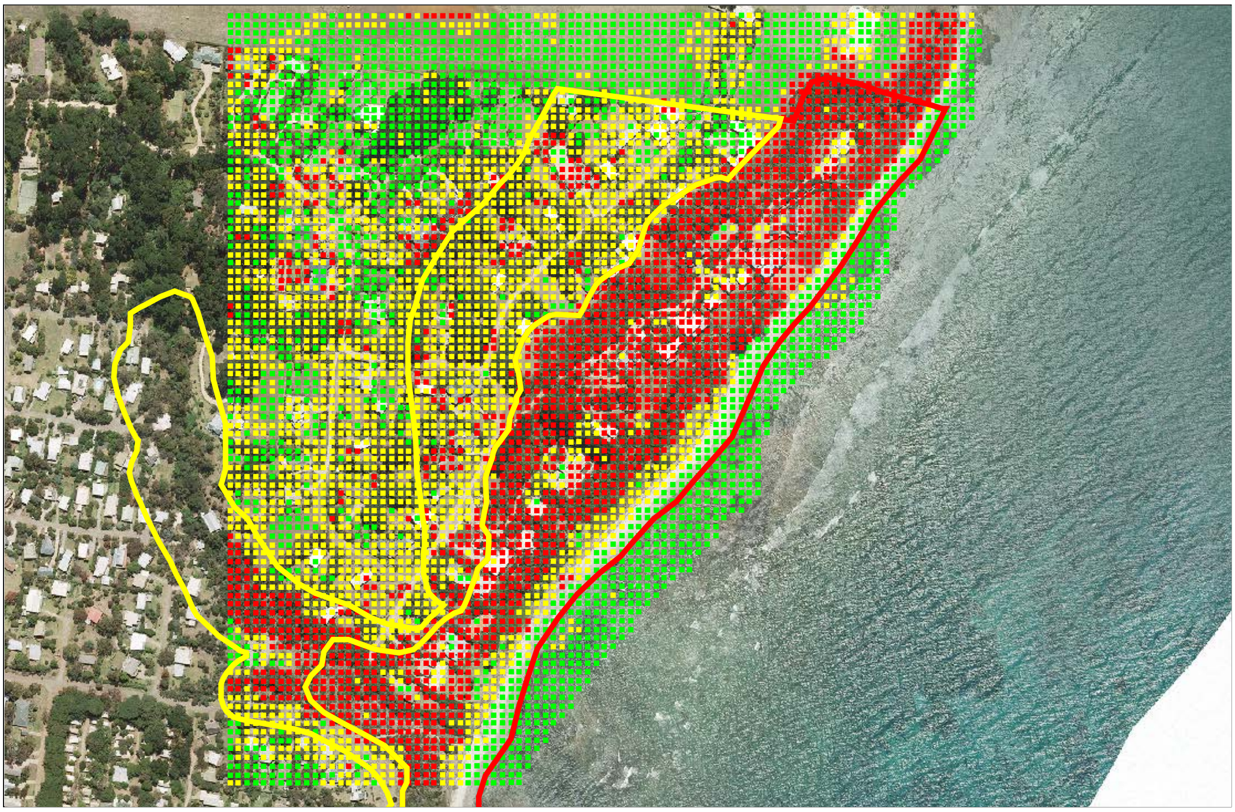


Figure 10-5: Flinders East - LP(2008A-2)

The model showed a good correlation with the boundaries of the red zone and a reasonable correlation with the yellow zone identified in LP(2008A) for the east of the Flinders township as can be seen above. One of the significant discrepancies is in the area of the creek. The GIS model predicts higher susceptibility than the field study, mostly as a result of the shallow bedrock which is not allowed for in the GIS model. Discrepancies outside of the yellow zone can be attributed to the LIDAR data including the slopes in the vicinity of features such as retaining walls and cuts.

Rosebud-Flinders Road

The investigation by Piper and Associates (1993) identified landslides in the vicinity of the creek and creep movement between the creek and Rosebud-Flinders Road. This site was used to verify the model for both the high/medium and medium/low boundaries for the Older Volcanics.

The results of the verification are shown in Figure 9-6 and are discussed below. The landslides in the vicinity of the creek are visible on aerial photography. The approximate limit of where these are visible on the aerial photography is marked with red lines on the figure. The results of the predictive model are shown as a grid of coloured squares with the red squares representing the predicted locations of high susceptibility and yellow squares representing the predicted locations of medium susceptibility.

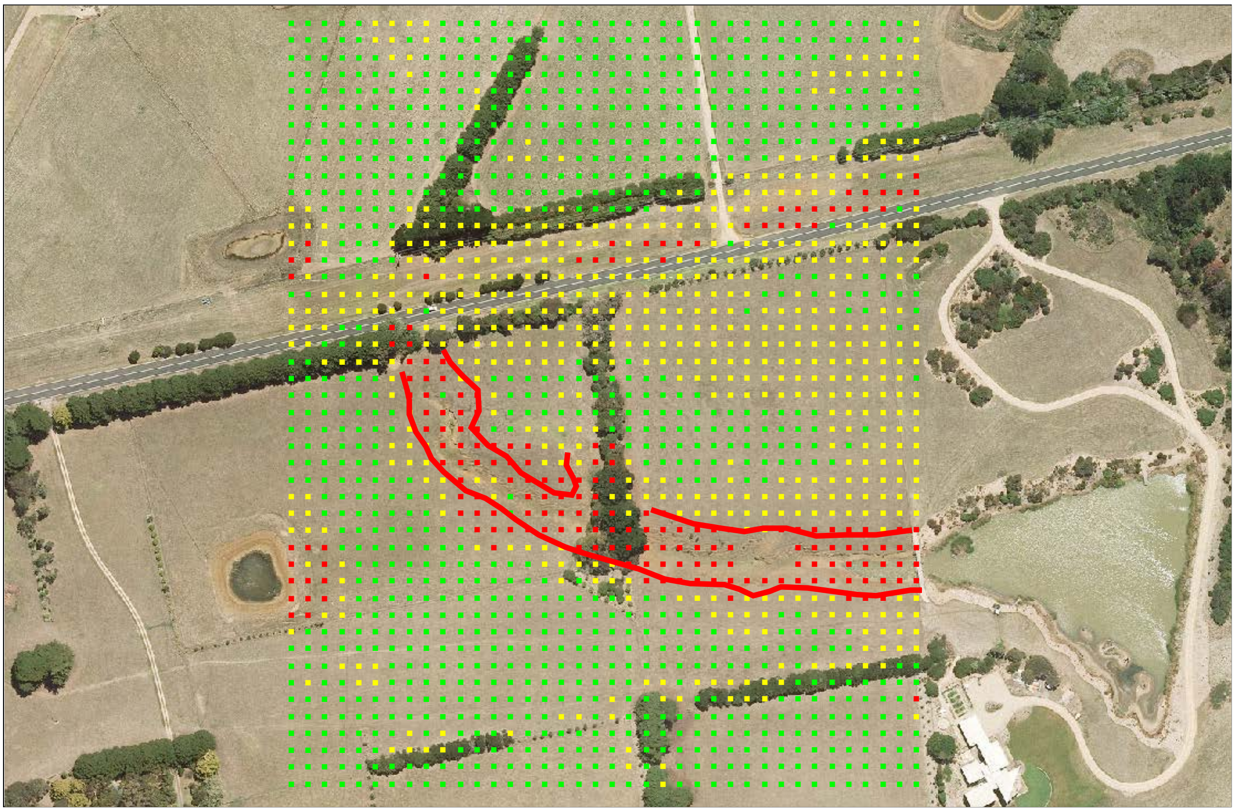


Figure 10-6: Rosebud Flinders Rd - PA (1993)

There appears to be a good correlation between the failures within the creek and the high susceptibility zone while the prediction of medium landslide susceptibility up slope of the creek also has a good correlation with the observed conditions.

Shoreham

As part of the Douglas Partners (2000) report and subsequent review by Piper & Associates a large landslide was identified in Shoreham. This landslide has been used to verify high/medium boundary for the model.

The results of the verification are shown in Figure 9-7 and are discussed below. The extent of the landslide as identified in aerial photography is shown with a red line. The results of the predictive model are shown as a grid of coloured squares with the red squares representing the predicted locations of high susceptibility.

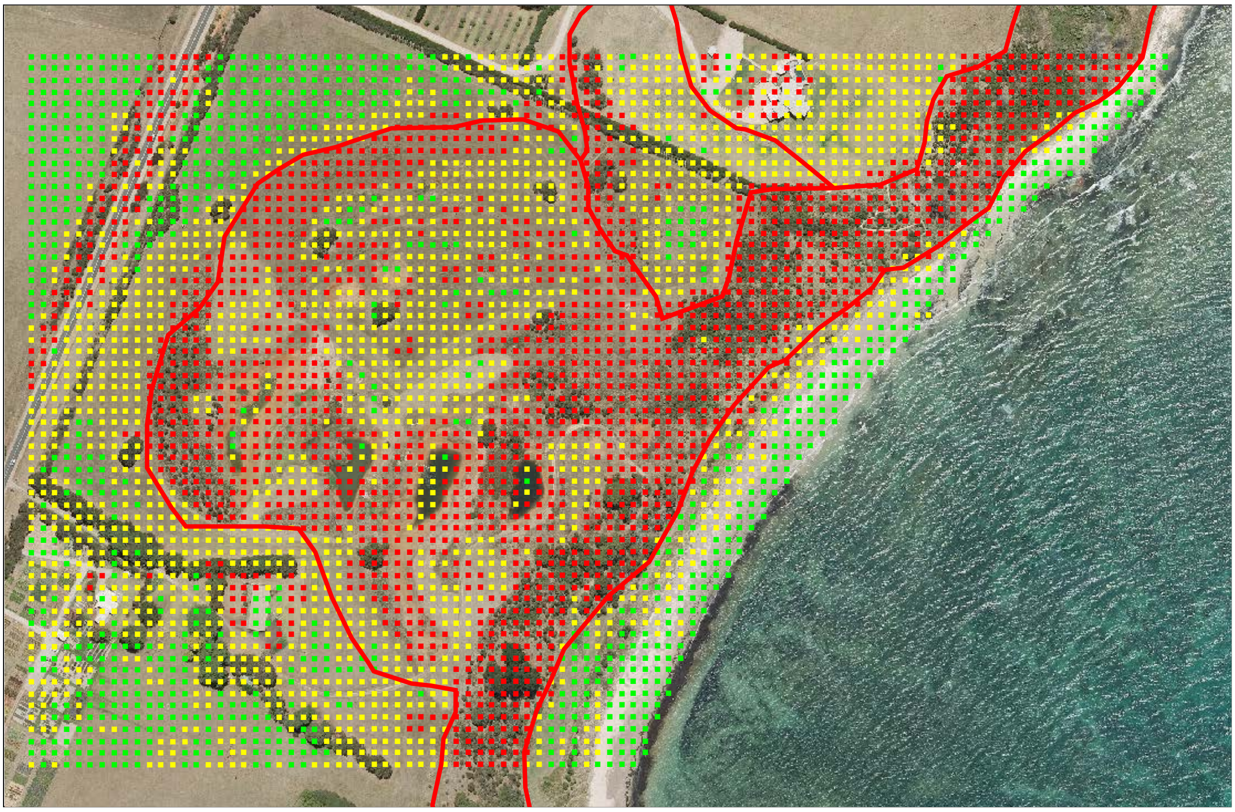


Figure 10-7: Shoreham - DP(2000)

The model shows a good correlation between the boundary of the observed landslide and the area of high landslide susceptibility from the GIS model. The model also predicted the impact of the cliff face and the presence of creep in the vicinity of the cliffs. However, the more level area within the landslip was not predicted and only areas of medium susceptibility were identified. For large landslides, the GIS model indicates areas of less susceptibility than should occur. However, this is largely overcome by adopting a ‘high’ susceptibility in areas of known landslip.

Somers

The cliffs along the Somers foreshore have been shown to have instability in various reports including LP(2010C) and aerial photography. These cliffs have been used to aid in verifying the landslide susceptibility model for the Older Volcanics.

The results of the verification are shown in Figure 9-8 and are discussed below. The extent of the areas of 'high landslip susceptibility' as identified in aerial photography is shown with a red line. The results of the predictive model are shown as a grid of coloured squares with the red squares representing the predicted locations of high susceptibility.

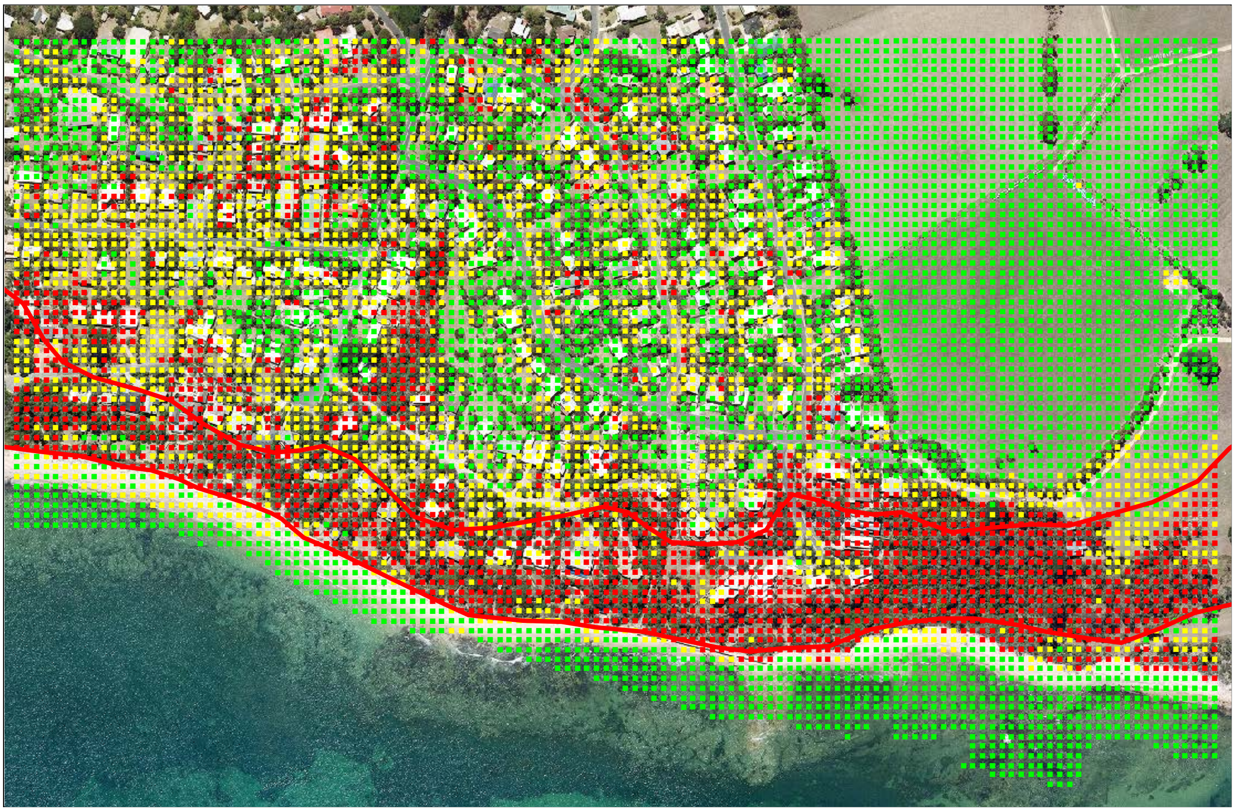


Figure 10-8: Somers - LP(2010C)

The model shows a reasonable correlation between the cliff line visible in aerial photography and the areas of high susceptibility. The model predicts slightly greater areas of 'high' landslip susceptibility, possibly as a result of the sensitivity of the digital terrain model The model also predicted the location of the former landslide at the western end of Western Park Road that was identified in LP(2010C).

10.6.4 Final Model

Based on the statistical analysis of the landslides identified in LP(2008A) the model has adopted the low/medium susceptibility boundary as having a slope of 14% and the medium/high susceptibility boundary as having a slope of 32%. The model was then verified by analysing the areas in the vicinity of several other landslides. The model was found to have a good correlation to the observed conditions. In large landslides, the model identified areas of 'medium' landslip susceptibility rather than 'high'. This is overcome in the study by adopting a 'high' landslip susceptibility with areas identified as landslips. Some areas were identified in the GIS study of being 'high' landslip susceptibility while the aerial study did not identify these.

This could be a result of a failure not occurring in these areas yet, shallow rock or more accurate survey data disclosing areas not previously identified.

Considering these values the susceptibility weighting for the Older Volcanics has been adopted as shown in Figure 9-9.

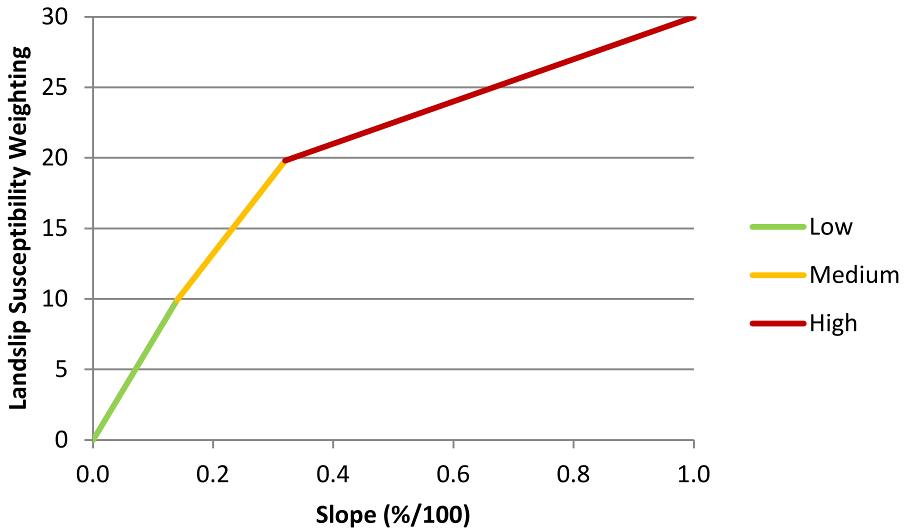


Figure 10-9: Slope vs. Susceptibility Weighting for Older Volcanics

10.7 Balcombe Clay

10.7.1 Refining of Geological Map for Balcombe Clay

The Balcombe clay geology is generally only shown on the geological maps to be within the creeks and cliffs where it is present at the surface. The Balcombe clays are mostly not at the surface and are only exposed where the natural surface mantle of the Baxter Sandstone has been eroded away.

Although the Balcombe clays are not at the surface, they have been shown to have an effect on slope stability when they are relatively shallow, or when the erosion causes the clays to be exposed in the toe of the slopes.

Therefore in order to allow a correct assessment of these areas, the geology maps used for the assessment have been altered to reflect the shallow Balcombe clays and not the overlying geology in the vicinity of the creeks and cliffs. The location of the boundary of the clays has been determined based on Gostin (1966). Gostin also indicates the approximate location of the Manyung fault, but more recent work has shown that the fault is actually a down-warp as shown at Ballar Creek by Piper & Associates (1995) and its location varies inland from that estimated by Gostin (1966).

10.7.2 Background Data

Landslides have been identified along the Mt Eliza coastline at numerous locations in studies including those by Gostin (1966), City of Frankston (1993), Coffey Geosciences Pty Ltd (1999), Lane Piper Pty Ltd (2007, 2008 & 2009) and Piper & Associates (1995, 2000 & 2006).

Landslides identified in the following studies were used in developing the predictive model and to confirm the results of the predictive model:

- Sunnyside Beach, Mt Eliza, Lane Piper – LP(2009A)
- Royston Court, Mt Eliza, Piper & Associates – PA(2000B)
- Norman Lodge, Mt Eliza, Lane Piper – LP(2007A)
- Ballar Creek, Mt Eliza, Coffey Geosciences – CG(1999)
- Davey's Bay, Mt Eliza, Piper & Associates – PA(2006A)
- Davey's Bay, Mt Eliza, Dennis, Price & Miller – CF(1993)
- Fishermans Beach, Mornington, Piper & Associates – PA(2003A)
- Mount Martha North Beach, Mt Martha, Lane Piper – LP(2009B)

The locations of these landslides are shown on the overhead photograph in the following figure.

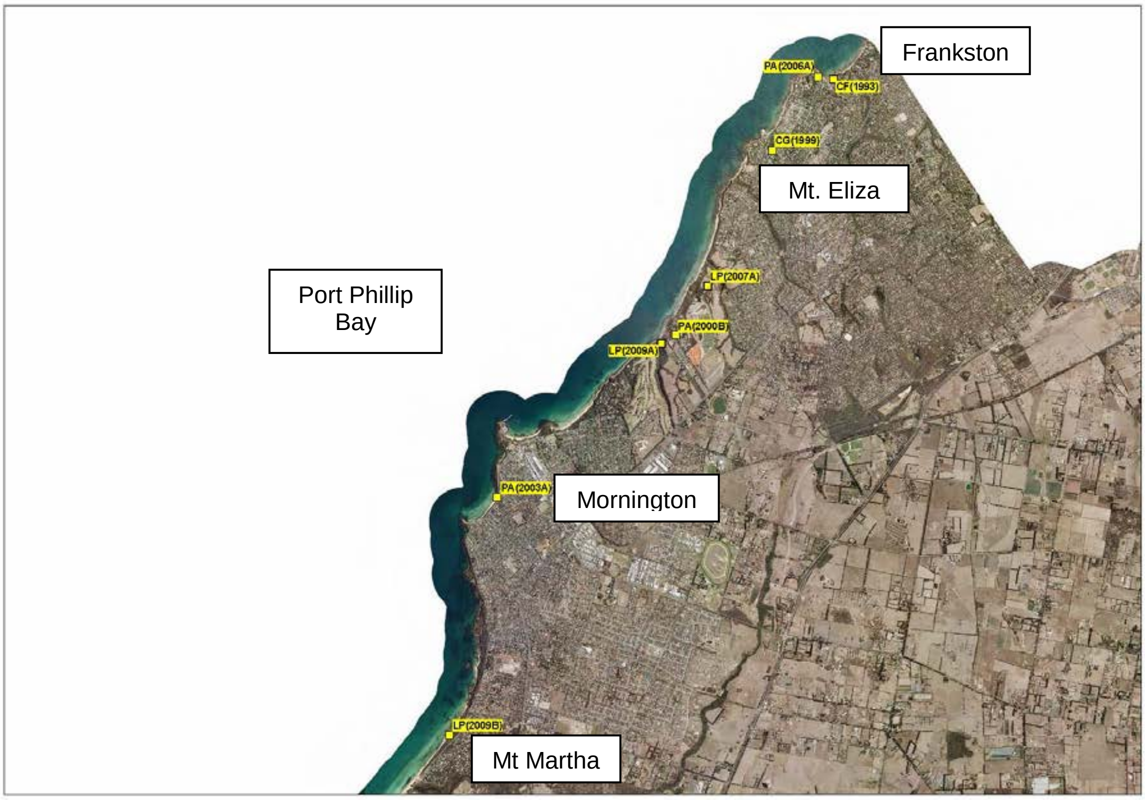


Figure 10-10: Sites used for Balcombe Clay Verification

10.7.3 Predictive Model

The predictive model for the landslide susceptibility of the Balcombe Clay geology was based on landslides identified in CG(1999), PA(2000B), LP(2007A) and LP(2009A).

The location of the landslides has been identified in the previous reports. The LIDAR data was used to refine the location of the landslide scarps.

The methodology outlined in Section 9.3 was then used to identify the boundaries for the high/medium and medium/low susceptibility.

An analysis of the data indicated that the slopes immediately up slope of the scarp varied between 5% and 36% while the slopes immediately down slope of the scarp varied between 126% and 110%. 181 points were used in the assessment. The intersection between the up-slope and down-slope curves was at 31% so this value was adopted as the high/medium boundary. The following figure shows the distribution of slopes that fell between the up slope and down slope side of the scarps.

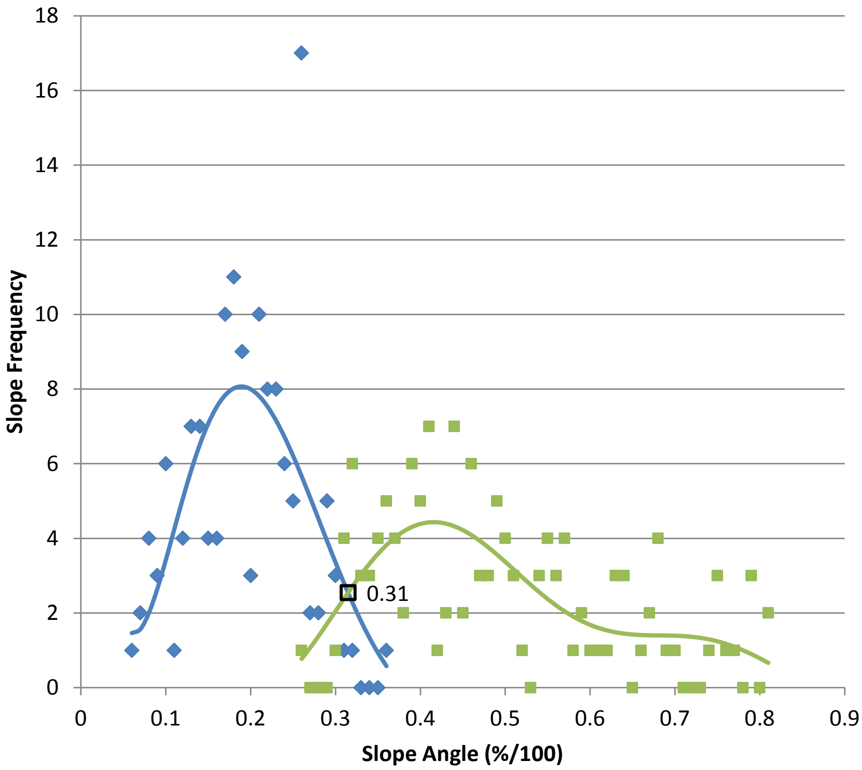


Figure 10-11: Balcombe Clay High/Medium Slope Distribution

Establishment of the moderate/low boundary for the Balcombe clay areas could not directly be established by identifying the location where creep movement was observed to commence. At the head scarps of the major landslides, there appears to be a sudden change from the regional slope to the landslide with no significant creep zone. However, creep has been observed to be occurring within the landslides themselves but the development of the residual condition within the Balcombe clays may be cause of this.

Along the banks of Ballar Creek, a creep zone was observed. This creep has been attributed to the movement of the overlying Baxter Sandstone soils on the underlying Balcombe Clays.

In order to determine the medium/low boundary, the slopes of the stable areas were compared to the slopes of identified creep areas.

An analysis of the data indicated that the slopes immediately up slope of the start of the creep zone varied between 5% and 14% while the slopes immediately down slope of the start of the creep zone varied between 12% and 58%. A total of 123 points were included in the assessment .The intersection between the up-slope and down-slope curves was at 14% so this value was adopted as the medium/low boundary. The following figure shows the distribution of slopes that fell between the up slope and down slope side of the creep zone boundary.

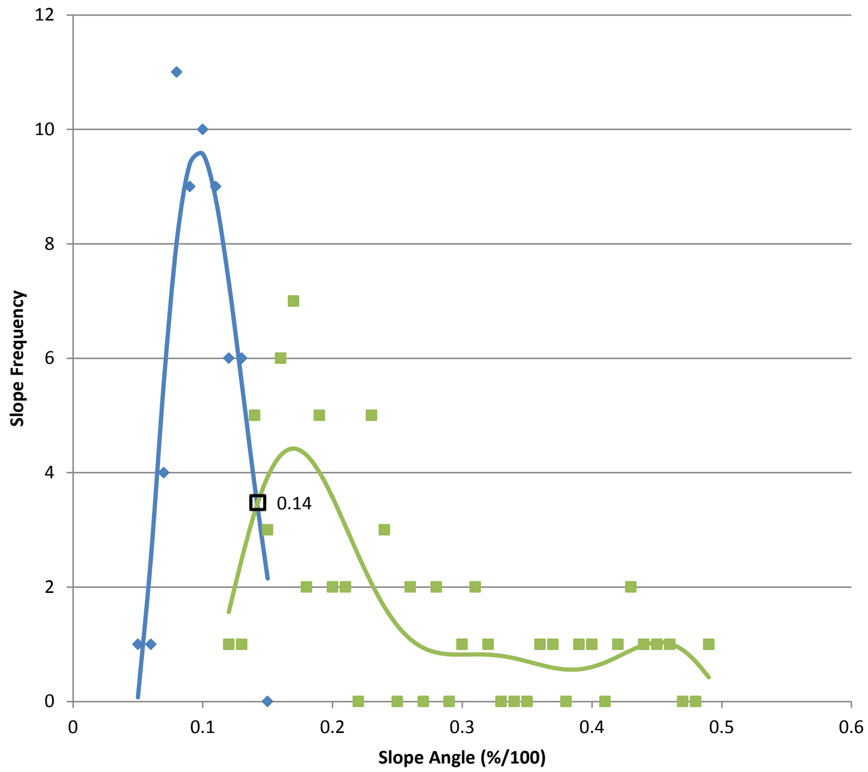


Figure 10-12: Balcombe Clay Medium/Low Slope Distribution

The downslope distribution is wide due to the variable history of the Balcombe clays. The Balcombe clays that have undergone prior shearing even as a result of the geological warping, will show a lower slope angle than a slope that has just failed. The adopted shear angle is at the lower end and represents a conservative assessment.

The slopes beyond the up slope influence of the landslide scarps were observed to have slopes in the range of 0-15% while creep was observed in areas with slopes down to 10-12% in the vicinity of Ballar Creek and within the existing landslides. Based on these values, the medium/low boundary was initially set at a slope of 12%.

10.7.4 Effect of Slope Aspect on Balcombe Clay Landslide Susceptibility

A review of the analysis results indicated that although the model provided a good correlation for the areas of known landslides, other areas that were known to be stable were being predicted to have a higher susceptibility than would be expected based on field observations.

When investigating landslides within Ballar Creek, Nielson (1995) & Piper & Associates (1995) determined that the areas of landslides affected by Balcombe clays are likely to be dominated by the direction of dip of the Manyung warp (fault) which generally dips to the north-west. Slopes that have Balcombe clays exposed in their face or at shallow depth that have a north to north-westerly aspect tend to be dominated by the impact of the Balcombe clay with reduced shear strength values as a result of previous shearing, often as low as the residual shear strength. As the aspect moves more northerly or westerly, that is away from the dip direction of the Manyung warp, the shear strength of the clays increases and can increase from the residual to the softened condition.

To allow for the effect of aspect on the slope in the Balcombe clay areas, the aspect factor specified earlier has been modified. An additional modification factor of 0.8 was applied to the calculated susceptibility values which were considered outside the influence of the Manyung Fault. This factor increased to 1 as the slope approached the N & W. The adopted modification factors are shown in the following table.

Table 10-2: Modification Factors for Slope Aspect (Balcombe Clays)

Aspect	Factor
N	1.0
NNE	0.9
NE	0.8
ENE	0.8
E	0.8
ESE	0.8
SE	0.8
SSE	0.8
S	0.8
SSW	0.8
SW	0.8
WSW	0.9
W	1.0
WNW	1.0
NW	1.0
NNW	1.0

10.7.5 Model Verification

Once the predictive model was established, the model was verified against the areas of identified slope instability mentioned in Section 9.7.2.

Sunnyside Beach and Royston Court

Investigations by Lane Piper (2009A), Piper & Associates (2000B) and others identified a large landslide at the north-western end of Sunnyside Road that extends from the south side of Sunnyside Road near the mouth of Manmangur Creek to the north end of Royston Court. The landslide identified in the reports was used to verify the predictive model for the landslide susceptibility for the Balcombe Clays.

The results of the verification are shown in Figure 9-13 and are discussed below. The boundary of the high susceptibility zone determined from aerial photographs and visual inspections is shown as a solid red line while the results of the predictive model are shown as a grid of coloured squares with the red squares representing the predicted locations of high susceptibility.

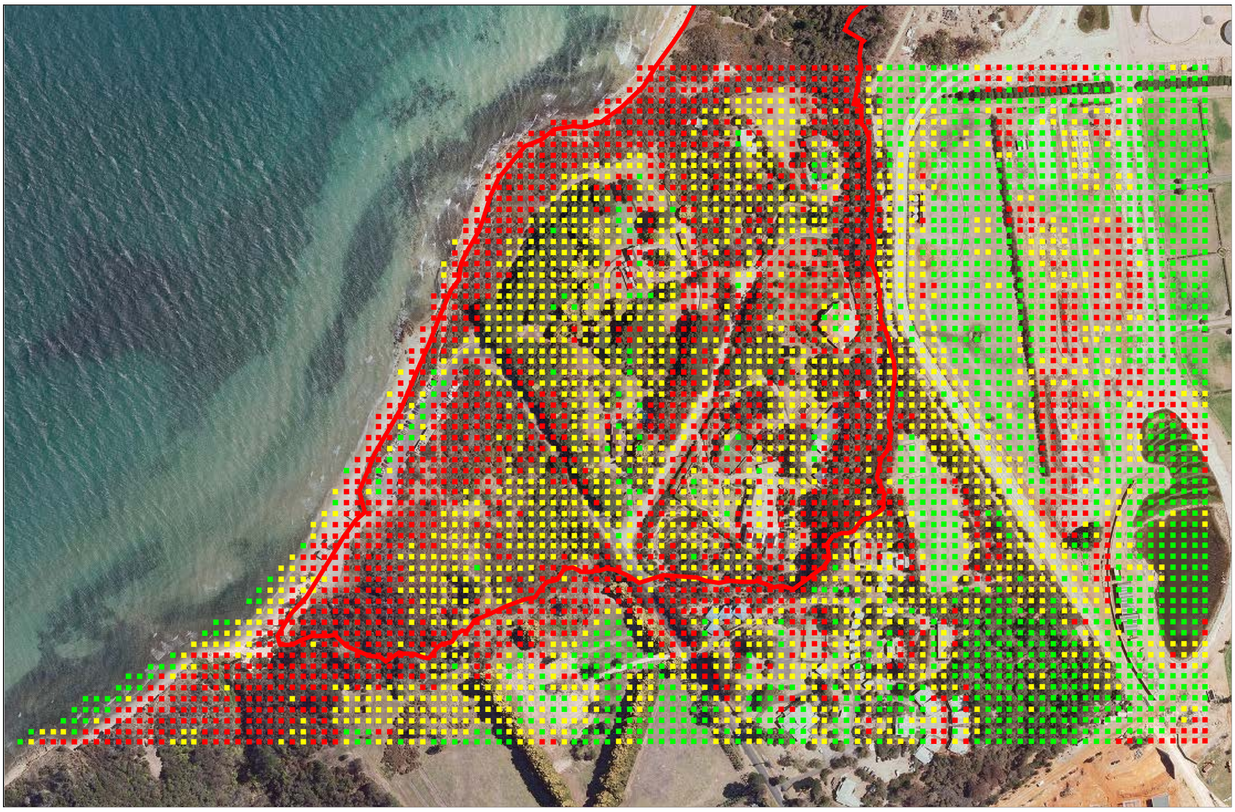


Figure 10-13: Sunnyside Beach and Royston Court - LP(2009A) & PA(2000B)

While the model shows a reasonable prediction with the landslip extremities, there are 'medium' landslip susceptible zones within the landslip itself. This was discussed in the previous section and is overcome within the model by measures indicated earlier.

Norman Myer Lodge

The landslide identified in LP(2007A) is very similar to the Sunnyside Road landslide which is located approximately 500m to the south. This landslide was also used to verify the appropriateness of the susceptibility model.

The results of the verification are shown in Figure 9-14 and are discussed below. The boundary of the high susceptibility zone determined from aerial photographs and visual inspections is shown as a solid red line while the results of the predictive model are shown as a grid of coloured squares with the red squares representing the predicted locations of high susceptibility.

Figure 10-14: Norman Myer Lodge LP(2007A)

The predictive model showed a very good correlation with the landslide identified at the Norman Myer Lodge property. The figure above shows the location of the landslides determined from aerial photography compared to the model. The landslide scarp is well predicted in the computer model, while a creep zone within the landslide was predicted, rather than a high susceptibility zone as discussed earlier. This creep zone was identified on the ground during the 2007 investigation.

Ballar Creek

Council has an existing Erosion Management Overlay (EMO) in place which was based on CG(1999) and added to earlier work by Piper and Associates. Considering that sections of the creek have been piped and filled it can be expected that model within those sections will not match the EMO zones. However, the downstream end of the creek was not backfilled. The EMO zones within downstream unfilled section of the creek have been used to verify the model.

The results of the verification are shown in Figure 9-15 and are discussed below. The boundaries of the high susceptibility zone and medium susceptibility zone determined from CG(1999) report are shown as a solid red and yellow lines while the results of the predictive model are shown as a grid of coloured squares.

Figure 10-15: Ballar Creek - CG(1999)

As previously discussed in the report, the Zones 3 and 4 from the Coffey report were defined as High Susceptibility, Zone 2 as Medium Susceptibility and Zone 1 as Low Susceptibility. Only the High and Medium Susceptibility zones from the Coffey report are shown in the figure. The comparison shows that the CG(1999) zonation for high susceptibility is well predicted by the model while medium susceptibility has a fair to poor correlation.

Davey's Bay

A shallow landslide of the cliff face was identified in PA(2006A). This cliff faces the north-east and does not appear to be affected by the Balcombe clays to the same extent as the north to north-westerly facing cliffs. Approximately 200m to the east of this shallow landslide CF(1993) identifies a larger deep seated landslide on a north-west facing cliff where the headscarp of the landslide coincides with the Manyung fault. This deep seated landslide is typical of the larger landslides in the Mt Eliza area.

These two landslides were used to confirm the model for the Balcombe Clays and more specifically for the effect of slope aspect on the model.

The results of the verification are shown in Figure 9-16 and are discussed below. The boundary of the high susceptibility zone determined from aerial photographs and visual inspections is shown as a solid red line while the results of the predictive model are shown as a grid of coloured squares with the red squares representing the predicted locations of high susceptibility.

Figure 10-16: Davey's Bay - PA(2006A) & CF(1993)

The predictive model showed a very good correlation with the head scarps of both landslides, but again not within the landslip itself.

Fisherman's Beach

A failure of the coastal cliffs at Fisherman's Beach in Mornington was identified in PA(2003). The Balcombe Clays are visible within the cliffs in this area. This landslide was used to confirm the model for the Balcombe Clays.

The results of the verification are shown in Figure 9-17 and are discussed below. The boundary of the high susceptibility zone determined from aerial photographs and visual inspections is shown as a solid red line while the results of the predictive model are shown as a grid of coloured squares with the red squares representing the predicted locations of high susceptibility.

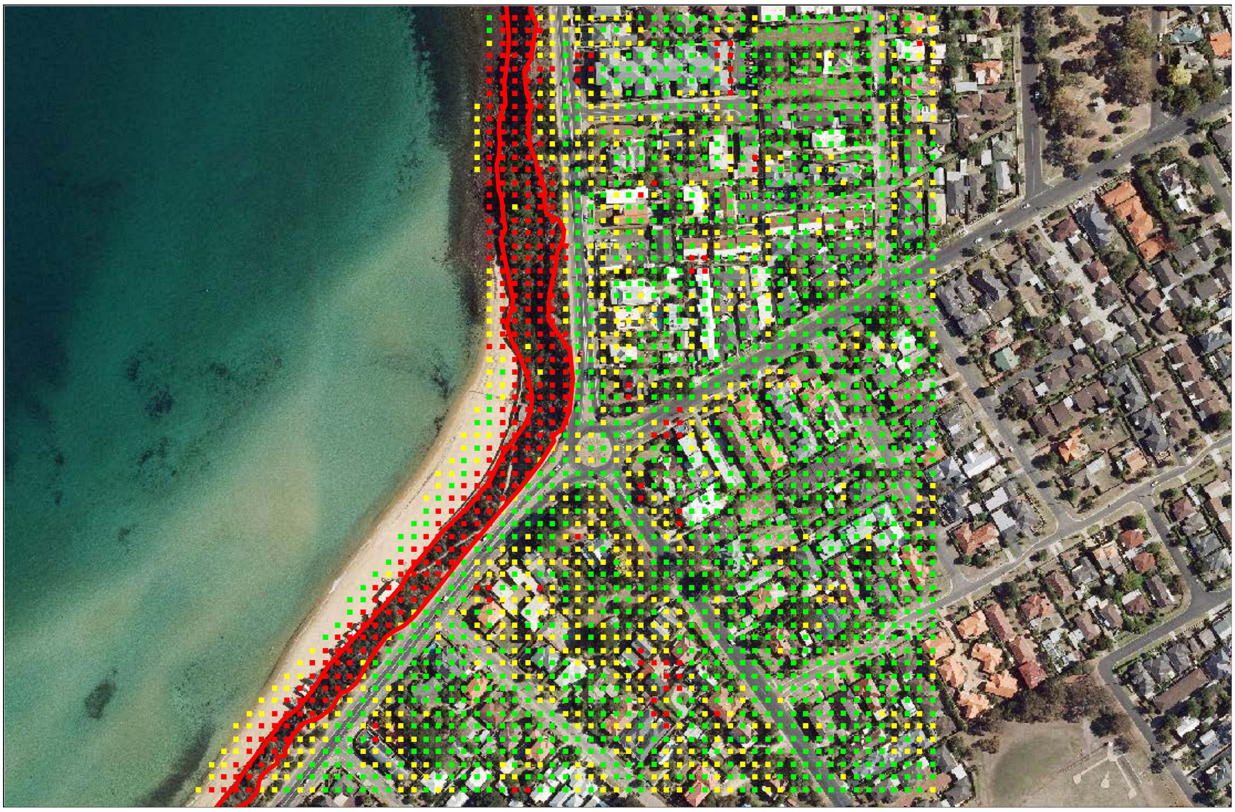


Figure 10-17: Fishermans Beach - PA(2003)

The model provides a good correlation to the observed conditions.

Mount Martha North

As part of investigations of the stability of the cliff face at Mount Martha North beach a large landslide was identified in LP(2009B) that extends from the beach almost to the Esplanade. Balcombe clays were identified at the toe of the landslide but to the south of the landslide the clays dipped below the level of the beach.

This landslide was also used to confirm the model for the Balcombe Clays. The results of the verification are shown in Figure 9-18 and are discussed below.

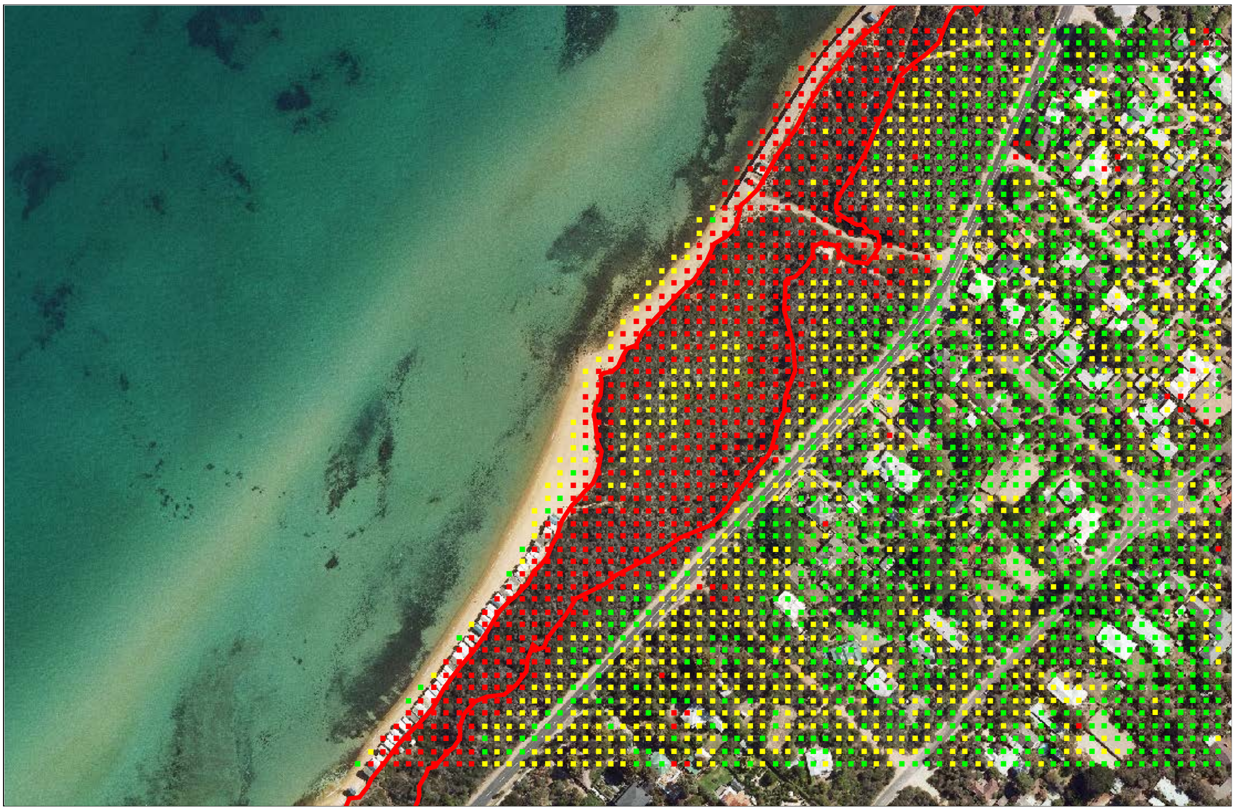


Figure 10-18: Mount Martha North - LP(2009B)

The landslide scarp location was predicted with a good correlation.

10.7.6 Final Model

Based on the statistical analysis of the landslides identified in CG(1999), PA(2000B), LP(2007A) and LP(2009A), the model has adopted the low/medium susceptibility boundary as having a slope of 14% and the medium/high susceptibility boundary as having a slope of 31%. The model was then verified by analysing the areas in the vicinity of several other landslides. The model was found to have a good correlation to the observed conditions. Overall the model was quite successful in the prediction and location of slope failures.

Considering these values the susceptibility weighting for the Balcombe Clays has been adopted as shown in Figure 9-19.

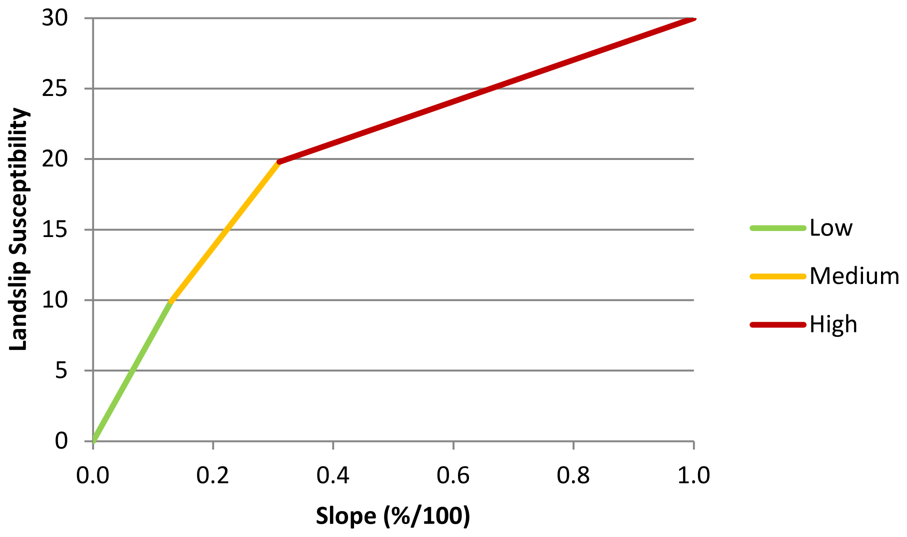


Figure 10-19: Slope vs. Susceptibility Weighting for Balcombe Clays

10.8 Baxter Sandstone

10.8.1 Background Data

The predictive model for the landslide susceptibility of the Baxter Sandstone geology was based on investigations of creek bank stability along Tanti Creek in Mornington (Lane Piper, 2010B). In addition, potential landslides that were identified along Balcombe Creek in Mount Martha as part of the aerial photography study in this investigation (LP-A1) were analysed to confirm the predictions of the model.

Instability along the creek banks and also up slope of the creek banks was observed in both studies. The slopes along Tanti Creek were used for the background data in creating the model for the Baxter Sandstone with the banks between Barkly Street and Stones Crossing being specifically targeted. In a section of Tanti Creek there is a zone that is subjected to artesian aquifer within a confined aquifer and is not representative of the Baxter Sandstone. In addition, the landslides along Balcombe Creek in the vicinity of Maude Street were also targeted.

The locations of these areas of instability are shown on the aerial photograph in the following figure.

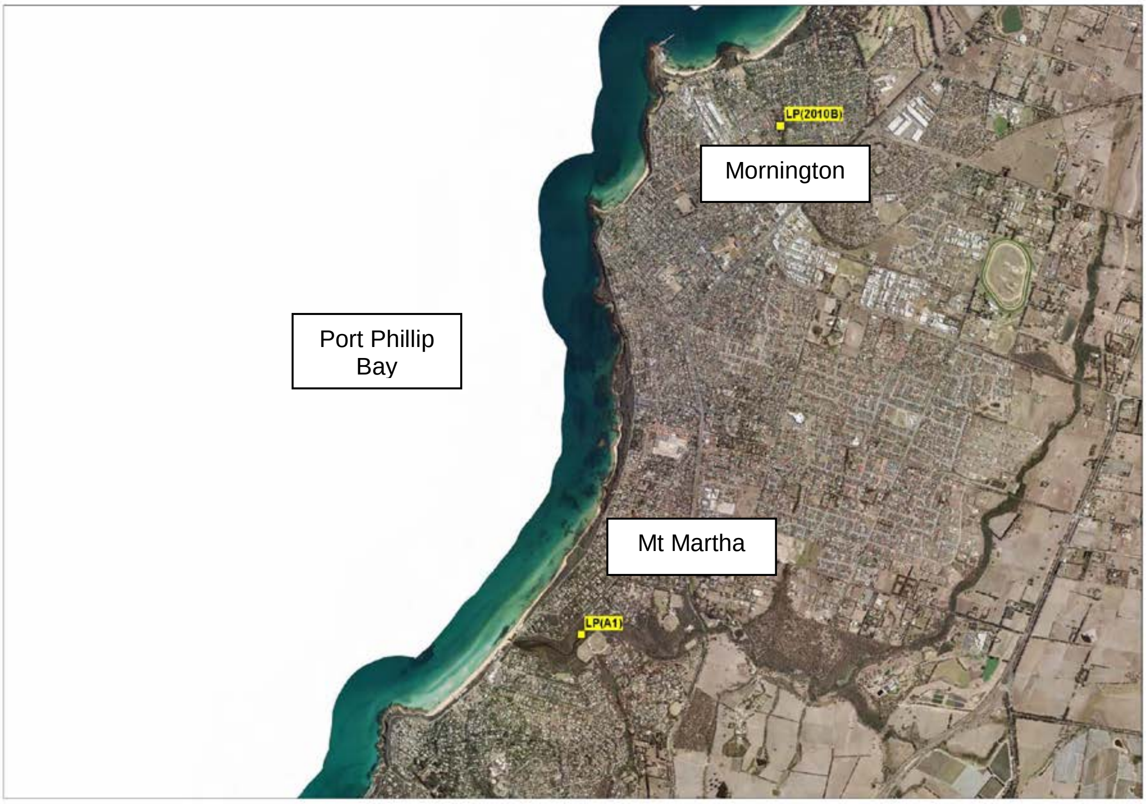


Figure 10-20: Sites used for Baxter Sandstone Verification

10.8.2 Predictive Model

As with the other geologies, the LIDAR data was used to refine the location of the landslides and creek bank instability.

The analysis of the data indicated that the slopes immediately up slope of the instability varied between 14% and 38% while the slopes immediately down slope of the instability varied between 29% and 100%. A total of 127 points were included in the assessment. The intersection between the up-slope and down-slope curves was at 37% so this value was adopted as the high/medium boundary. The following figure shows the distribution of slopes that fell between the up slope and down slope side of the scarps.

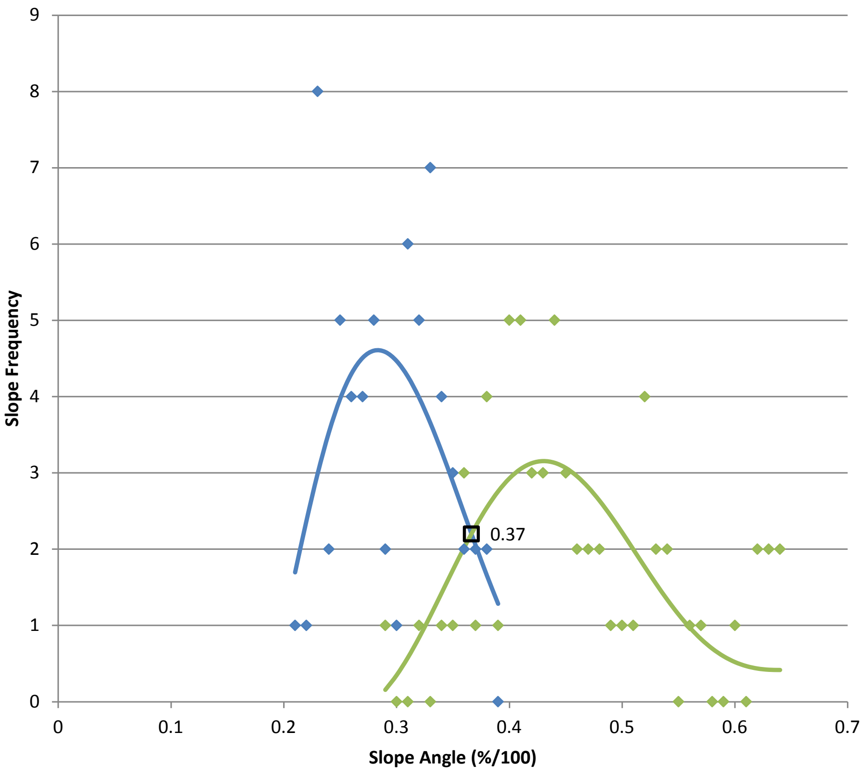


Figure 10-21: Baxter Sandstone High/Medium Slope Distribution

The potential creep zone in the Baxter Sandstone geology area was identified as a change in grade from the consistent slopes at a distance from the creeks to a gradual fall towards the creeks.

An analysis of the data of some 80 slopes indicated that the slopes immediately up slope of the start of the creep zone varied between 6% and 18% while the slopes immediately down slope of the start of the creep zone varied between 14% and 41%. The intersection between the up-slope and down-slope curves was at 16% so this value was adopted as the medium/low boundary. The following figure shows the distribution of slopes that fell between the up slope and down slope side of the creep zone boundary.

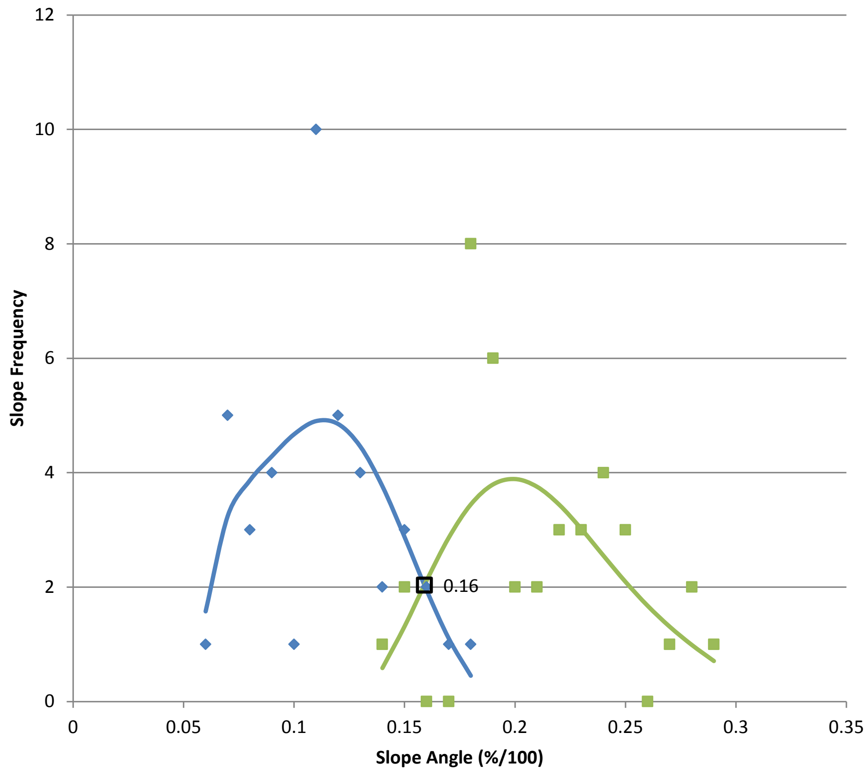


Figure 10-22: Baxter Sandstone Medium/Low Slope Distribution

10.8.3 Model Verification

Once the predictive model was established, the model was verified against the known observations for Tanti Creek and Balcombe Creek mentioned in Section 9.8.1.

Tanti Creek

The investigation of Tanti Creek reported in LP(2010B) identified areas of instability along the creek generally typified by shallow failures of the creek banks except in the vicinity of Stones Crossing where artesian pressures resulted in deeper seated failures of the areas in the vicinity of the creek. The section of Tanti Creek between Barkly Street and Stones Crossing was used to verify the model for the Baxter Sandstone soils.

The results of the verification are shown in Figure 9-23 and are discussed below.

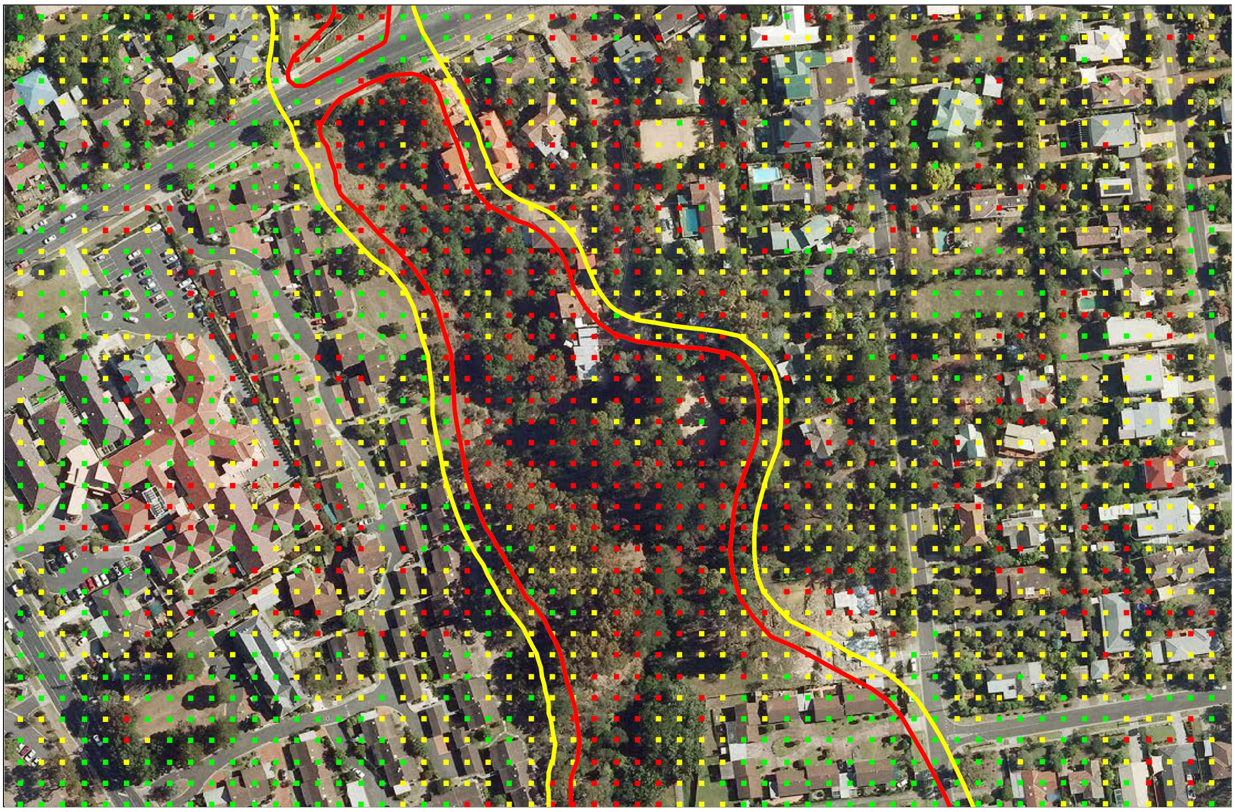


Figure 10-23: Tanti Creek - LP(2010B)

There was a good correlation between the model and the boundaries for the EMO identified in Lane Piper (2010B) in the vicinity of Barkly Street. The model predicted well the high susceptibility zones within the creek and the medium susceptibility zones where creep was observed up slope of the creek. The model also predicted that there were zones of high landslide susceptibility outside of the EMO, especially to the east of the creek to the south of Barkly Street.

The discrepancy between the model and the EMO in the south of the picture is due to the aforementioned shallow artesian pressures resulting in landslides at a much shallower slope than that would normally be expected for the Baxter Sandstone soils.

Balcombe Creek

As part of the review of aerial photographs conducted for this report, several landslides and areas of slope instability were identified in the vicinity of Balcombe Creek. As there was only a limited number of published geotechnical reports that provide details of slope instability for Baxter Sandstone soils on the Mornington Peninsula which are not influenced by the Balcombe Clays it was considered prudent to use these areas of instability to confirm the landslide susceptibility model.

According to the geology may of the area (Western Port, 1:63,360), the creek banks on the northern side of Balcombe Creek are dominated by the Baxter Sandstone geology while the southern banks are dominated by other geologies.

The results of the verification are shown in Figure 9-24 and are discussed below.

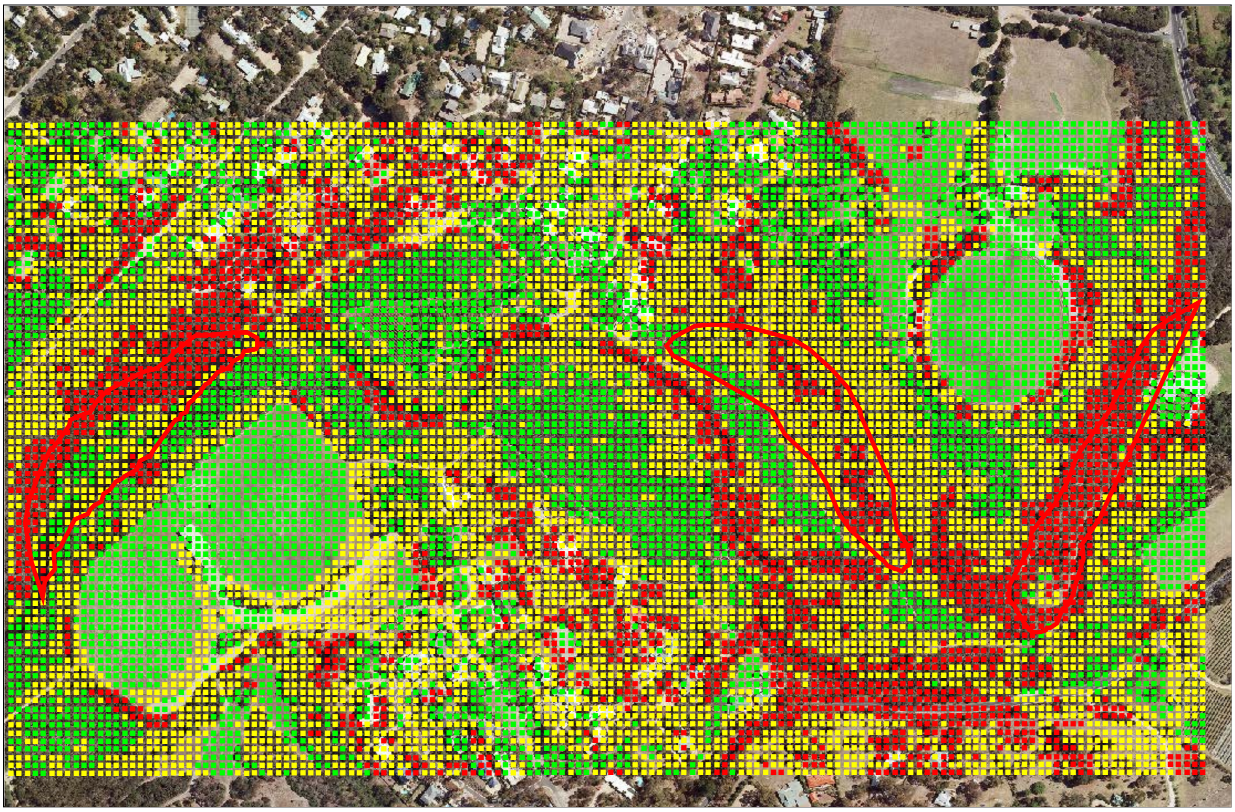


Figure 10-24: Balcombe Creek - LP(A1)

The predictive model indicates a good correlation for two of the three identified potential landslides. The third potential landslide, shown second from the right was generally shown to be in an area of moderate susceptibility. This slope was significantly less steep than the other slopes.

10.8.4 Final Model

The final model which was based on the statistical analysis of the landslides identified in LP(2010B) has adopted the low/medium susceptibility boundary as having a slope of 16% and the medium/high susceptibility boundary as having a slope of 37%. The model was then verified by analysing the areas in the vicinity of several other landslides. The model was found to have a good correlation to the observed conditions. Overall the model was successful in the prediction and location of slope failures.

Considering these values the susceptibility weighting for the Baxter Sandstone soils has been adopted as shown in Figure 9-25.

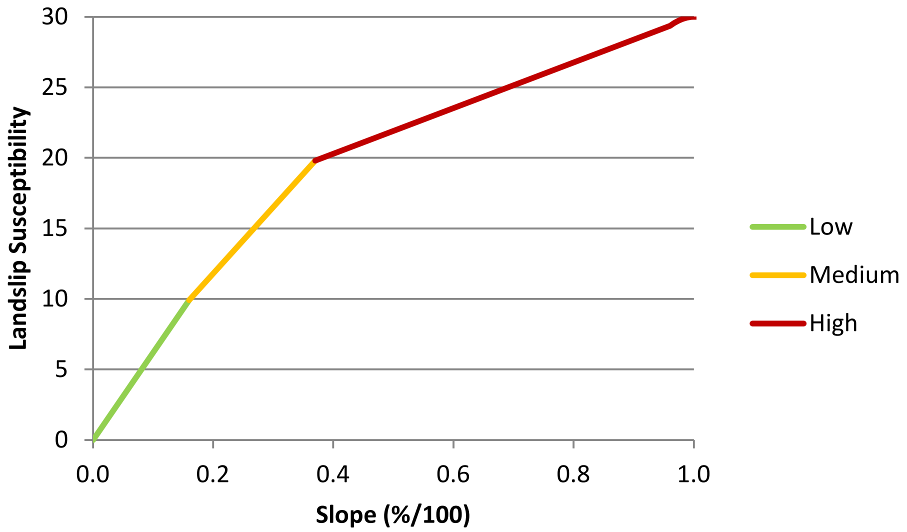


Figure 10-25: Slope vs. Susceptibility Weighting for Baxter Sandstone

The model will not predict failures at flatter slopes where there is elevated groundwater or artesian aquifer. A geotechnical investigation is required to establish if there is elevated groundwater which may result in a slope failure at a flatter slope than predicted above.

10.9 Devonian Granite

10.9.1 Background Data

The predictive model and confirmation analysis for the landslide susceptibility of the Devonian Granite geology was based on landslides identified in the following reports:

- Davey's Bay, Dennis, Price & Miller – CF(1993)
- Anthony's Nose, Piper & Associates – PA(2000A)
- Dromana Foreshore, Lane Piper – LP(2010A)
- McCrae, Lane Piper – LP(2007B)

In addition, the slopes measured by LIDAR before a recent landslide (September 2010) in the vicinity of the Esplanade and Ellerina Road in Mount Martha have been used in the confirmation analysis, LP(A2).

The locations of these areas of instability are shown on the overhead photograph in the following figure.

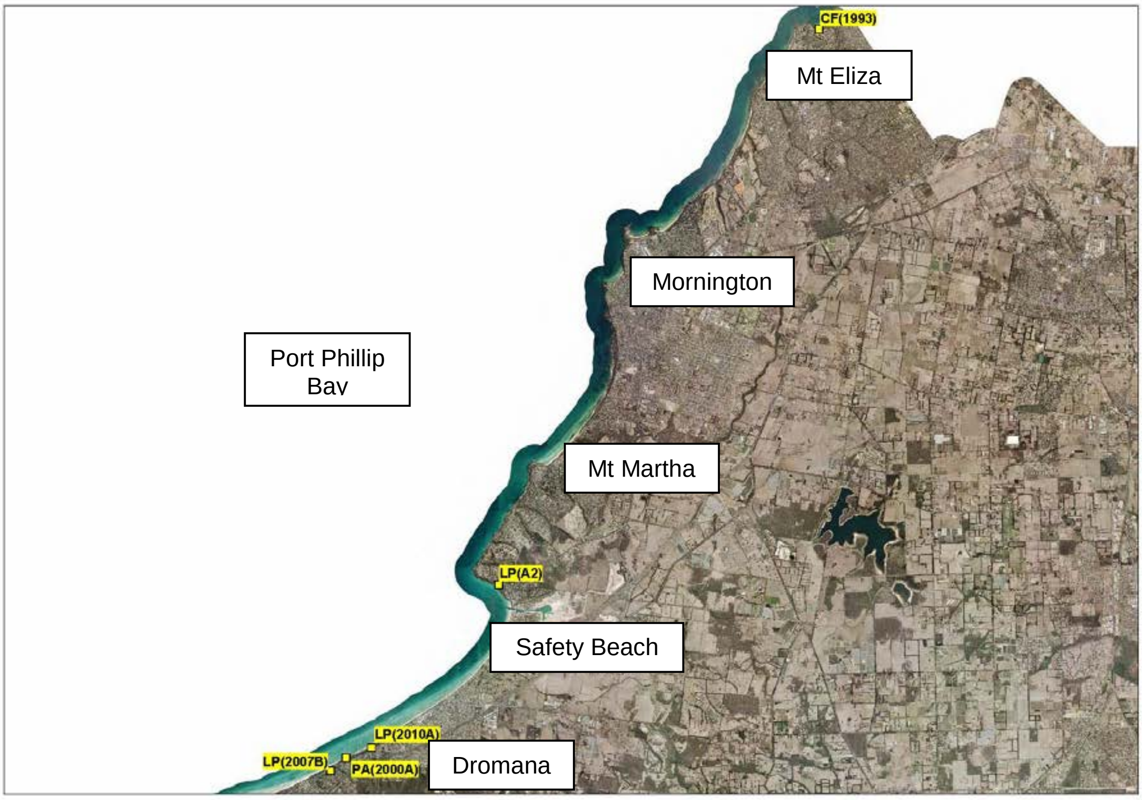


Figure 10-26: Sites used for Devonian Granite Verification

10.9.2 Predictive Model

The LIDAR data was again used to refine the location of the areas of slope instability.

The analysis of the data indicated that the slopes immediately up slope of the scarp varied between 7% and 50% while the slopes immediately down slope of the scarp varied between 46% and 154%. A total of 143 points were included in the assessment. The intersection between the up-slope and down-slope curves was at 50% so this value was adopted as the high/medium boundary. The following figure shows the distribution of slopes that fell between the up slope and down slope side of the scarps.

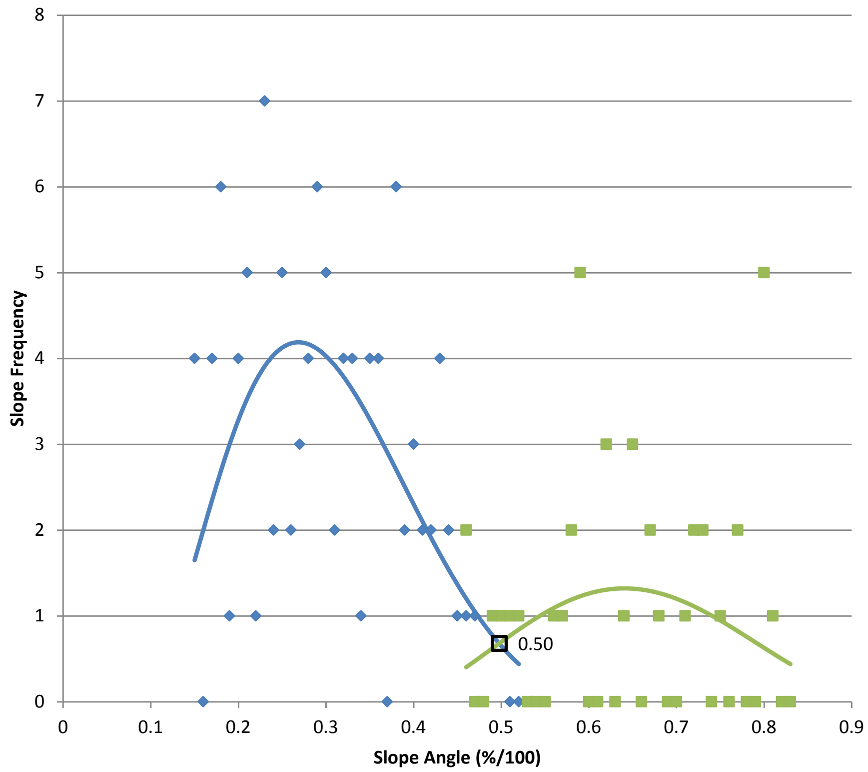


Figure 10-27: Devonian Granite High/Medium Slope Distribution

The location of the creep zone within Latrobe Reserve which was identified in the Lane Piper (2010A) report was identified in the LIDAR data as a distinct change in grade between the open areas in the vicinity of Latrobe Parade and the vegetated areas closer to the cliff face.

An analysis of the data indicated that the slopes immediately up slope of the start of the creep zone varied between 7% and 23% while the slopes immediately down slope of the start of the creep zone varied between 23% and 112%. A total of 32 points were included in the assessment. The intersection between the up-slope and down-slope curves was at 25% so this value was adopted as the medium/low boundary. The following figure shows the distribution of slopes that fell between the up slope and down slope side of the creep zone boundary.

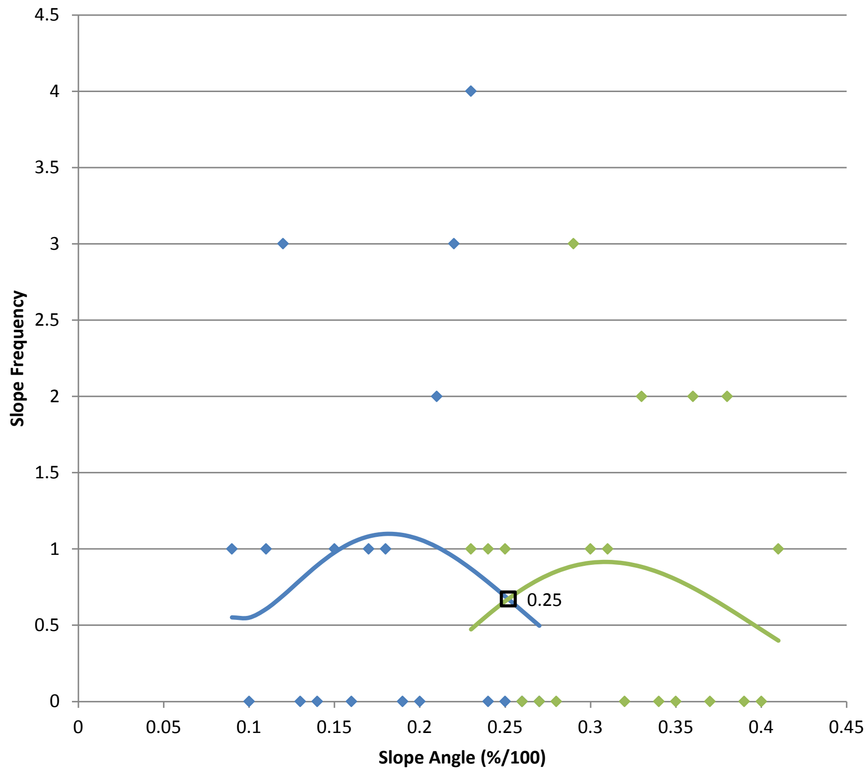


Figure 10-28: Devonian Granite Medium/Low Slope Distribution

10.9.3 Model Verification

Once the predictive model was established, the model was verified against the known observations for Tanti Creek and Balcombe Creek mentioned in Section 9.9.1.

Davey's Bay

As previously discussed, the CF(1993) landslide is complex in that the displaced zone of the landslide is within Baxter Sandstone soils overlying Balcombe Clay while the scarp of the landslide is within Devonian Granite. The scarp of the CF(2003) landslide was used for confirmation of the Devonian Granite predictions.

The results of the verification are shown in Figure 9-29 and are discussed below. Only the part of the model that corresponds to the landslide scarp and upslope of the landslide is shown.

Figure 10-29: Davey's Bay - CF(1993)

The model correctly identified the granitic headscarp of the Davey's Bay landslide and also instability within the Kackeraboite Creek. The model indicates that up slope of the creek banks there are also areas of high landslide susceptibility.

Anthony's Nose

The granitic cliffs at Anthony's Nose have been shown to have instability issues in PA(2000A). These cliffs were used to aid in the verification of the model for the granitic soils.

The results of the verification are shown in Figure 9-30 and are discussed below.

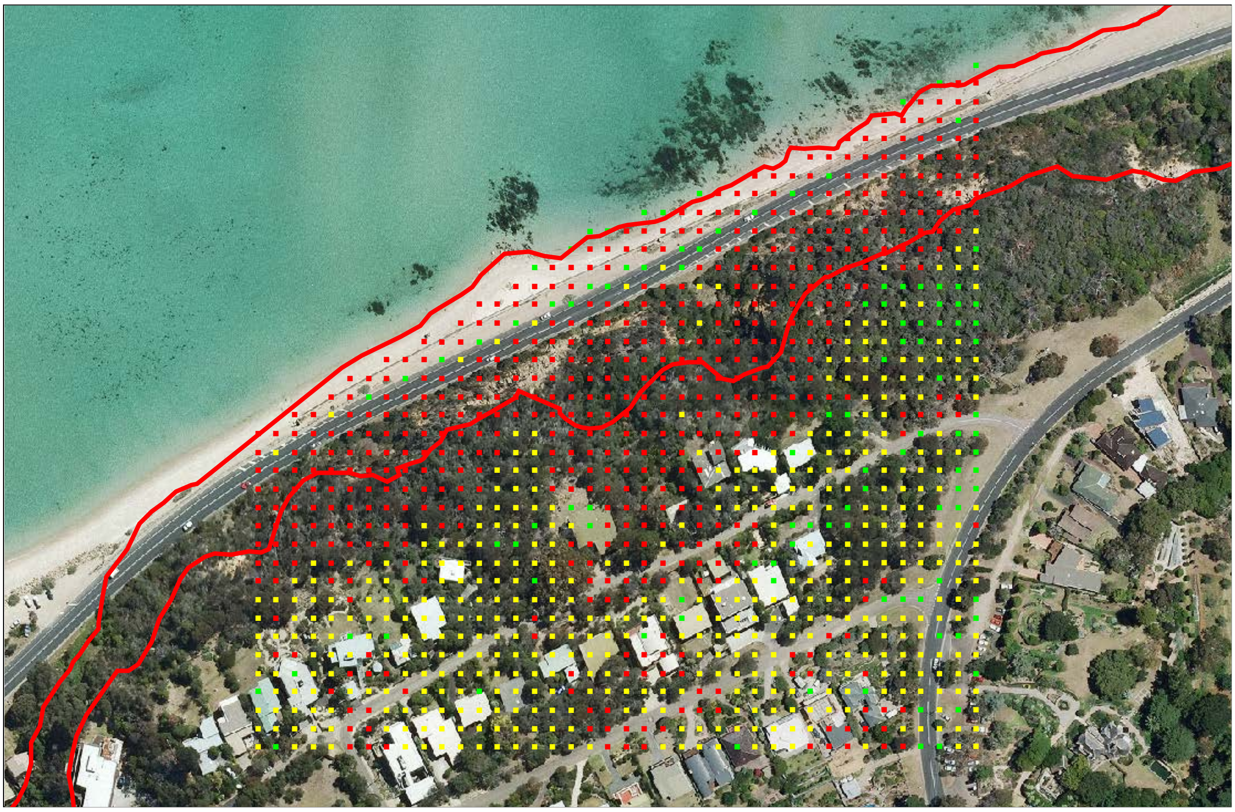


Figure 10-30: Anthony's Nose PA(2000A)

The model predicts the location of the cliff face as well as highlighting areas of high landslide susceptibility further upslope from the cliff face that were not readily identifiable in the aerial photographs possibly hidden by vegetation.

Dromana Foreshore

The cliffs at Anthony's Nose continue along the foreshore of Dromana to the east. These cliffs were investigated and reported in LP(2010A). These cliffs were again used to aid in the verification of the model for the granitic soils.

The results of the verification are shown in Figure 9-31 and are discussed below.

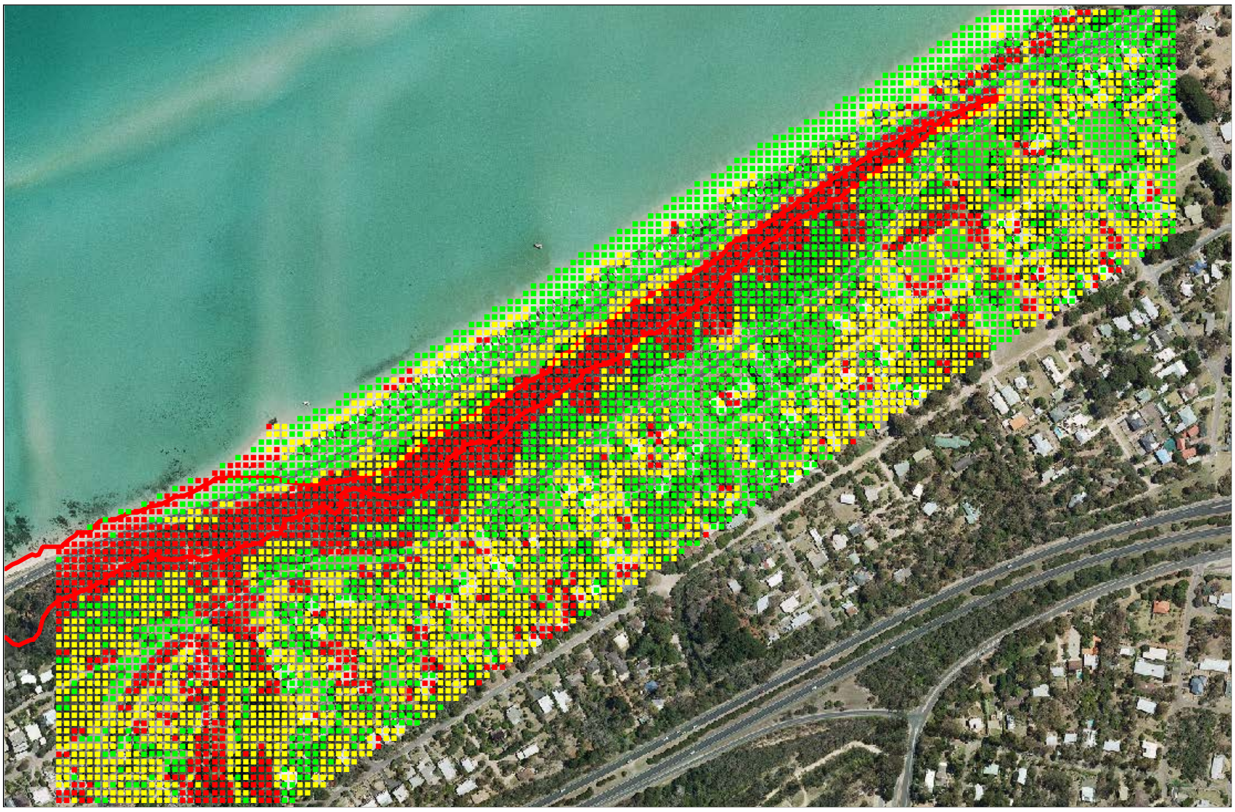


Figure 10-31: Dromana Foreshore - LP(2010A)

The model is well correlated with the aerial photography including where the cliff face ends in the north east of the figure. The model has also correctly identified the gullies along the foreshore to be highly susceptible to landslides as was observed on the ground during the Lane Piper (2010A) investigation.

McCrae

The cliffs at McCrae have been shown to be unstable in the past due to both natural and man-made causes. The cliff gully between The Eyrie and Nepean Highway was one of these areas that was the subject of the LP(2007B) report. The cliffs and gully were again used to aid in the verification of the model for the granitic soils.

The results of the verification are shown in Figure 9-32 and are discussed below.

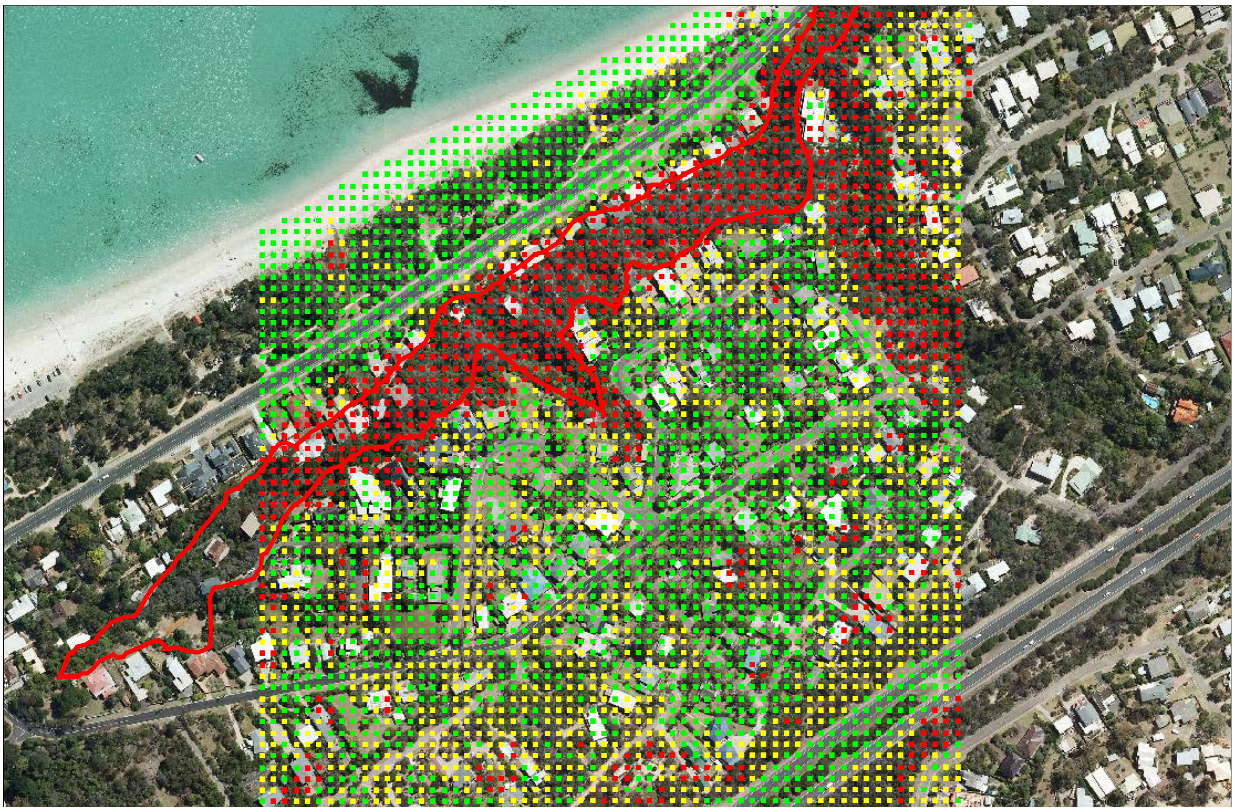


Figure 10-32: McCrae - LP(2007B)

The results of the predictive model very closely match the areas identified in the aerial photography. The main differences between the two being that the model has correctly identified gullies that have been identified to have stability issues in the field.

Mount Martha

In addition to the areas of instability identified in published reports another area of potential instability in the vicinity of Ellerina Road in Mount Martha was used to verify the model.

The results of the verification are shown in Figure 9-33 and are discussed below.

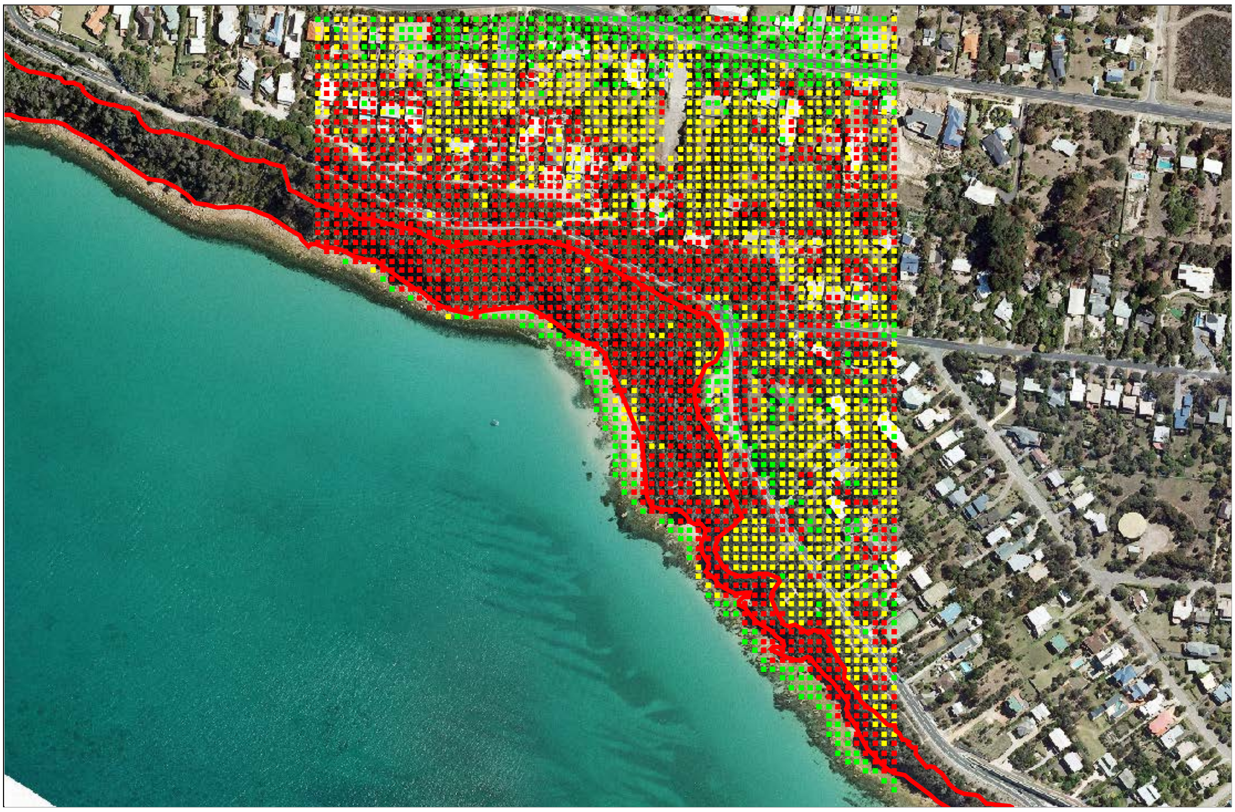


Figure 10-33: Mount Martha - LP(A2)

The above figure shows the foreshore in the vicinity of the intersection of the Esplanade and Ellerina Road in Mount Martha. A landslide has recently occurred in this area. The predictive model has correctly identified the area of potential instability highlighted by the aerial photographs. The model upslope of the foreshore and the Esplanade is also shown to have a high to moderate level of landslide susceptibility. Creep movement has anecdotally been reported in this area, which, if present, would confirm the appropriateness of the moderate susceptibility rating predicted by the model.

10.9.4 Final Model

The final model which was based on the statistical analysis of the landslides identified in various reports has adopted the low/medium susceptibility boundary as having a slope of 25% and the medium/high susceptibility boundary as having a slope of 50%. The model was then verified by analysing the areas in the vicinity of several other landslides. The model was found to have a good correlation to the observed conditions. Overall the model was successful in the prediction and location of slope failures.

Considering these values the susceptibility weighting for the Devonian Granite soils has been adopted as shown in Figure 9-34.

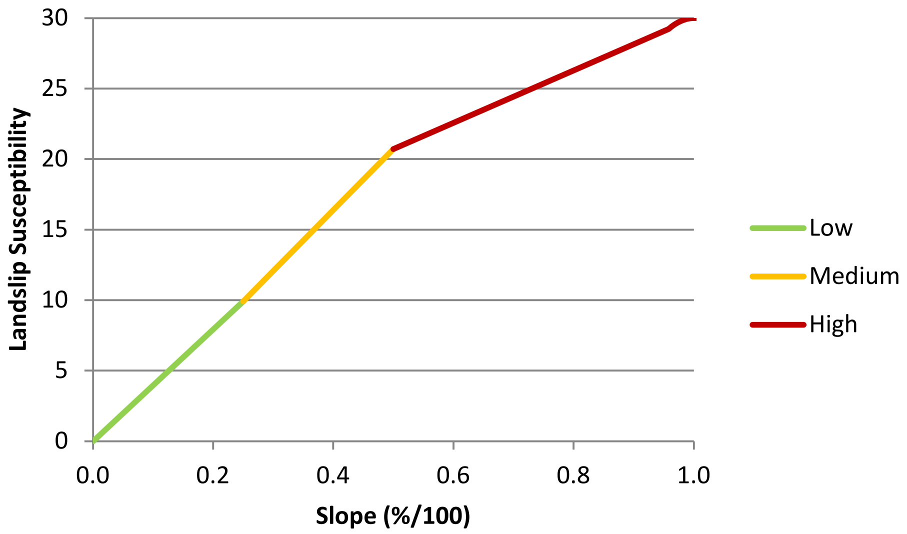


Figure 10-34: Slope vs. Susceptibility Weighting for Devonian Granite

10.10 Quaternary Alluvial Soils

10.10.1 Establishment of Model

Little information is available on landslides within the alluvial soils on the peninsula as generally the alluvial soils are located in flatter areas and landslides in the creek banks were often associated with the neighbouring geology.

As the alluvial soils are often high plasticity clays, a predictive model was set up based on another high plasticity soil, specifically the Tertiary Basalts.

10.11 Quaternary Sands

As previously discussed in Section 4.9, the Quaternary sands are dominated by calcareous sands. The calcareous sands are typified by variable interbedded layers of hard concretionary limestone and loose sands. The stability of slopes that are formed within this geology is highly dependent on the degree of cementation of the sands. Where there is little cementation within the sands, the slope is unlikely to be stable much beyond the natural angle of repose of the loose sands with shallow arcuate and translational failures being more common. Where there is a high degree of cementation, the slope may be able to stand near vertical with the main form of slope failure being toppling failures due to undermining of the cemented layers by erosion of the loose sand layers.

The model for the landslide susceptibility of the Quaternary sand geology was based on the actual measured slopes in areas of known instability. Due to the variable nature of the cemented sands, significant variation in slope stability can be expected and slopes may be stable at much greater slopes than that predicted by the model.

10.11.1 Background Data

The model for the landslide susceptibility of the Quaternary sand geology was based on areas of potential instability identified in the following reports:

- 3804 Pt. Nepean Rd, Portsea, CivilTest – CT(2006)

- Point Franklin, Parsons Brinckerhoff – PB(2003)
- 3550 Pt. Nepean Rd, Portsea, Piper & Associates – PA(2006C)
- Rye Backbeach, Piper & Associates – PA(2006B)

The location of the areas used to develop the model are shown below.

Figure 10-35: Sites used for Quaternary Sand Verification

10.11.2 Predictive Model

The LIDAR data was again used to identify the areas where there was a significant change in slope.

The analysis of the data indicated that the slopes immediately up slope of the scarp varied between 14% and 52% while the slopes immediately down slope of the scarp varied between 35% and 260%. A total of 139 points were included in the assessment. The intersection between the up-slope and down-slope curves was at 54% so this value was adopted as the high/medium boundary. The following figure shows the distribution of slopes that fell between the up slope and down slope side of the scarps.

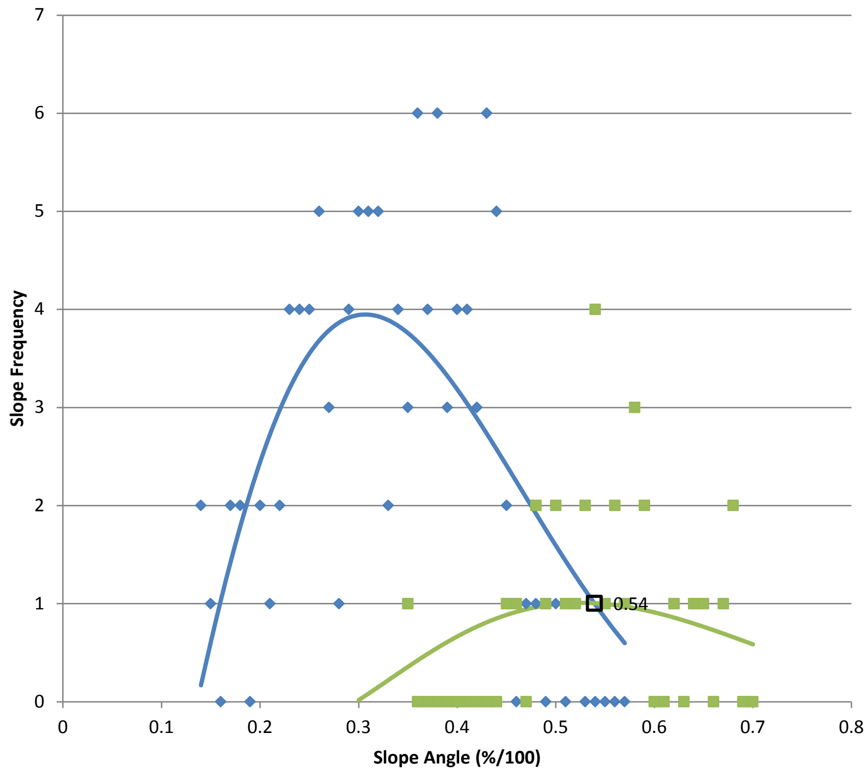


Figure 10-36: Quaternary Sands High/Medium Slope Distribution

The slopes in the vicinity of the cliffs for the Aeolian sands typically have a sudden change between the gradual slopes away from the cliffs to the steep slopes of the cliffs. Due to this it was difficult to establish a distinct creep zone as often there is not one with sand dunes. As such, the value of 25% adopted for the low/medium boundary for the granitic sands was initially adopted to be confirmed by the verification analysis.

10.11.3 Model Verification

Once the predictive model was established, the model was verified against the known observations identified in CT(2006), PB(2003), PA(2006C and PA(2006B) mentioned in Section 9.11.1.

3804 Pt. Nepean Road

The site at 3804 Pt. Nepean Road is typical of the Portsea foreshore area. Very steep coastal cliff comprising cemented sands line the foreshore while upslope of the cliffs the area is relatively flat. Instability of these cliffs is typically confined to the immediate vicinity with regression of the cliffs being slow.

The results of the verification are shown in Figure 9-37 and are discussed below.

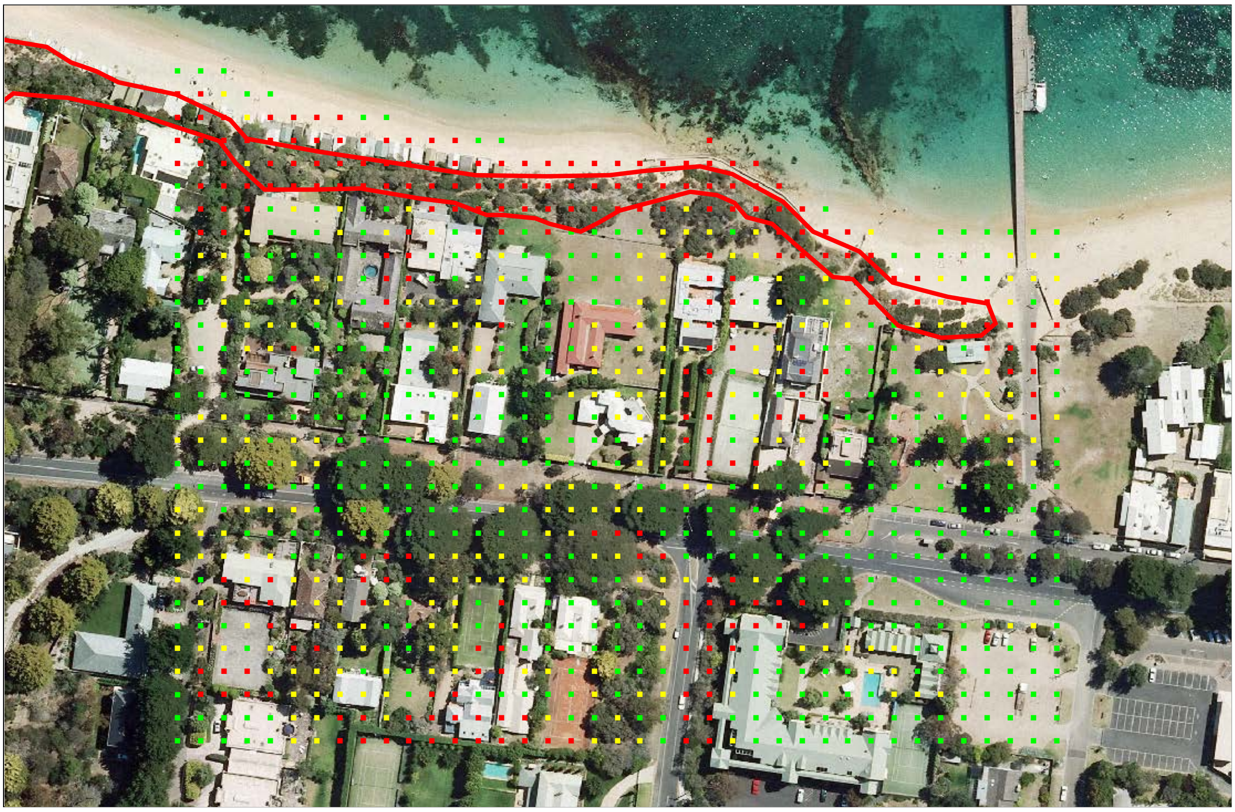


Figure 10-37: 3804 Pt. Nepean Road - CT(2006)

The model shows a good correlation with the observed conditions with the high susceptibility areas generally being confined to the cliffs.

The high susceptibility zones identified away from the cliffs appear to be the result of retaining walls or gullies.

Point Franklin

The cliffs at Point Franklin are similar to those mentioned above with steep cliffs lining the foreshore and relative flat areas up slope of the cliffs.

The results of the verification are shown in Figure 9-38 and are discussed below.

Figure 10-38: Point Franklin - PB(2003)

The model again provides a good correlation with the aerial photography. A discrepancy between the model and aerial photography in the upper part of the figure is due to a steep hill on the coast line which slopes away from the coast.

3550 Pt. Nepean Road

This site is another typical example of the steep coastal cliffs in the area. The results of the verification are shown in Figure 9-38 and are discussed below.

Figure 10-39: 3550 Pt. Nepean Road - PA(2006C)

The model has again provided a mostly good correlation with the model.

Rye Backbeach

While the geology at Rye backbeach also comprises Quaternary aged sands, the low cementation of the sands in this area has resulted in cliffs comprising steep dunes rather than a single near vertical cliff. Aerial photography of the area identified that the areas of high landslide susceptibility extend significantly further inland than within Port Philip Bay.

The results of the verification are shown in Figure 9-38 and are discussed below.

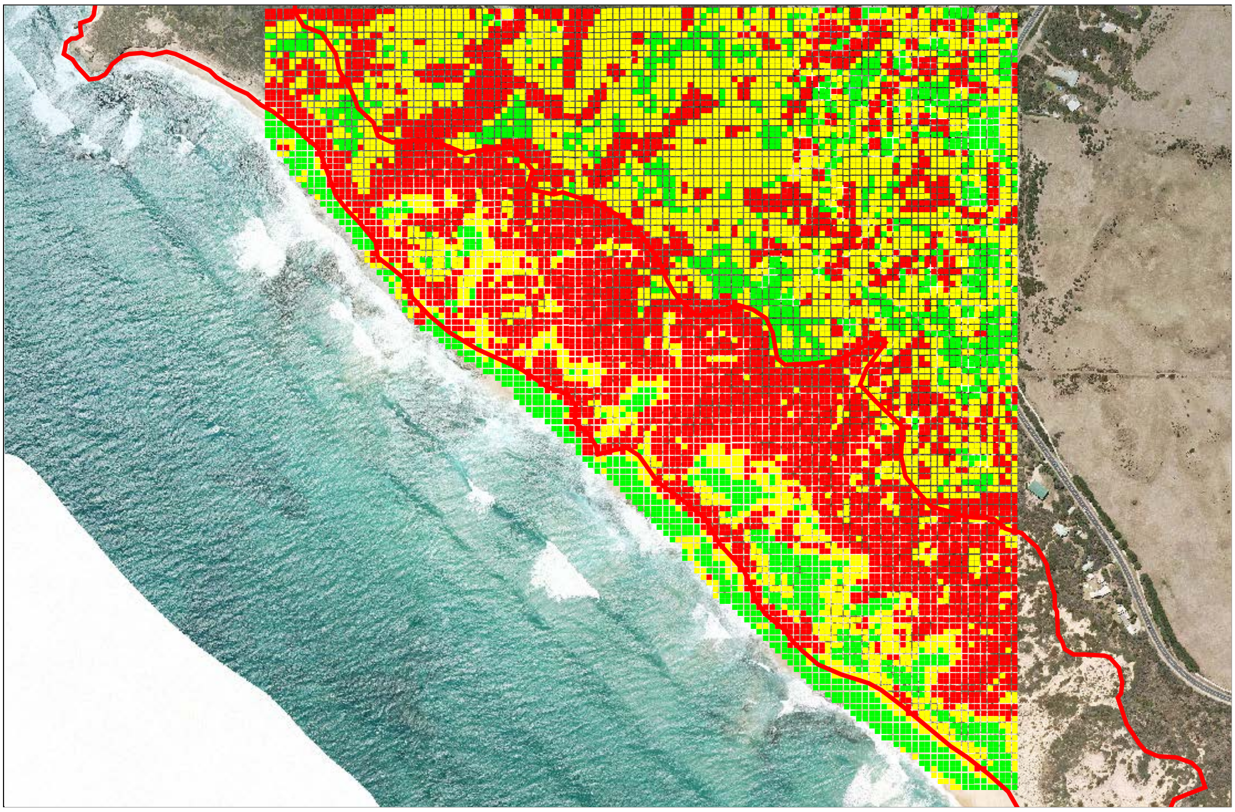


Figure 10-40: Rye Backbeach - PA(2006B)

The PA(2006B) investigation was conducted inland from the coast away from the foreshore. The investigation indicated that there was minimal evidence of slope instability on that site but that localised instability of steeper slopes in the future could not be precluded. In the area of the investigation (the upper right third of the figure), the model has generally predicted a moderate landslide susceptibility which is consistent with the findings of the investigation.

In addition to the previous investigation, the aerial photographs were studied for the foreshore. The area of high landslide susceptibility identified in the aerial photography is shown on the left. The results of the model are consistent with the aerial photography.

10.11.4 Final Model

The final model which was based on the statistical analysis of the landslides identified in various reports has adopted the low/medium susceptibility boundary as having a slope of 25% and the medium/high susceptibility boundary as having a slope of 54%.

The model was then verified by analysing the areas in the vicinity of several other areas of instability. The model was found to have a good correlation for the medium/high boundary.

While minimal data was available for correlating the low/medium boundary, the results did seem to provide a reasonable correlation, but there is insufficient data for this to be confirmed and should be regarded as interim stability zone rather than a creep zone.

Overall the model was successful in the prediction and location of slope failures.

Considering these values the susceptibility weighting for the Quaternary sands has been adopted as shown in Figure 9-41.

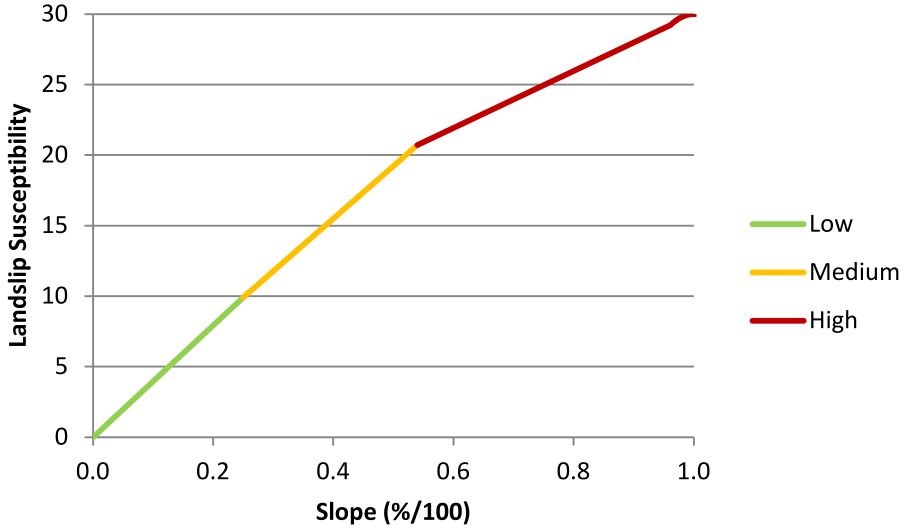


Figure 10-41: Slope vs. Susceptibility Weighting for Quaternary Sands

10.12 Siltstone Soils

10.12.1 Background Data

Landslides in the siltstone geologies of the Peninsula are rare. However, some have occurred in northern parts of the peninsula in the vicinity of Two Bays Road and Canadian Bay Road.

Two areas of known slope instability have been used in developing the predictive model for the siltstone as follows:

- Two Bays Road, Mt Eliza, Piper & Associates – PA(1996)
- Moorooduc Quarry, Piper & Associates – PA(2000C)

Both of these landslides are a result of slope steeping from mankind activities. The locations of the areas of instability are shown on the following figure.

Figure 10-42: Sites used for Siltstone Verification

10.12.2 Predictive Model

The slopes in the vicinity of Two Bays Road was used to establish the predictive model.

The analysis of the Two Bays data indicated that the slopes in the vicinity of and immediately up slope of the area of instability varied between 35% and 86% while the slopes further up slope from the area of instability varied between 12% and 43%. A total of 66 points were included in the assessment. A break in slope was visible in contours of the area at the boundary between these two zones. The intersection between the up-slope and down-slope curves was at 36% so this value was adopted as the high/medium boundary.

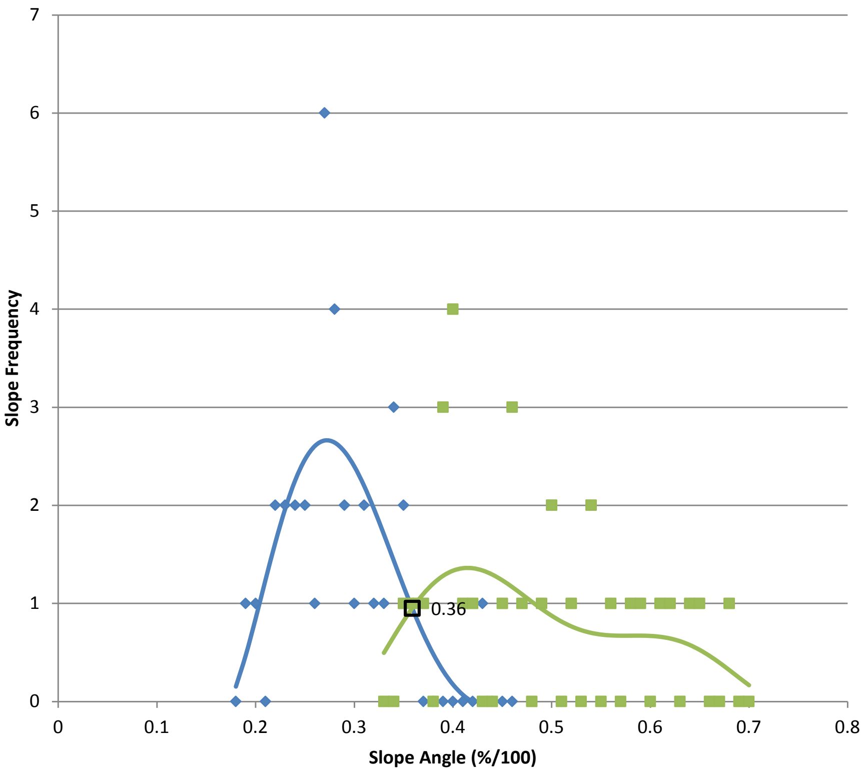


Figure 10-43: Siltstone High/Medium Slope Distribution

An intermediate zone was identified between the area of the instability and further up-slope where the slope flattens off. A break in slope was identifiable between the intermediate zone and the flatter area. The slopes on the down slope side of the break in slope had slopes of between 18% and 71% while the slopes in the flatter area had slopes of between 8% and 20%. A total of 103 points were included in the assessment. The intersection between the up-slope and down-slope curves was at 18% so this value was adopted as the medium/low boundary.

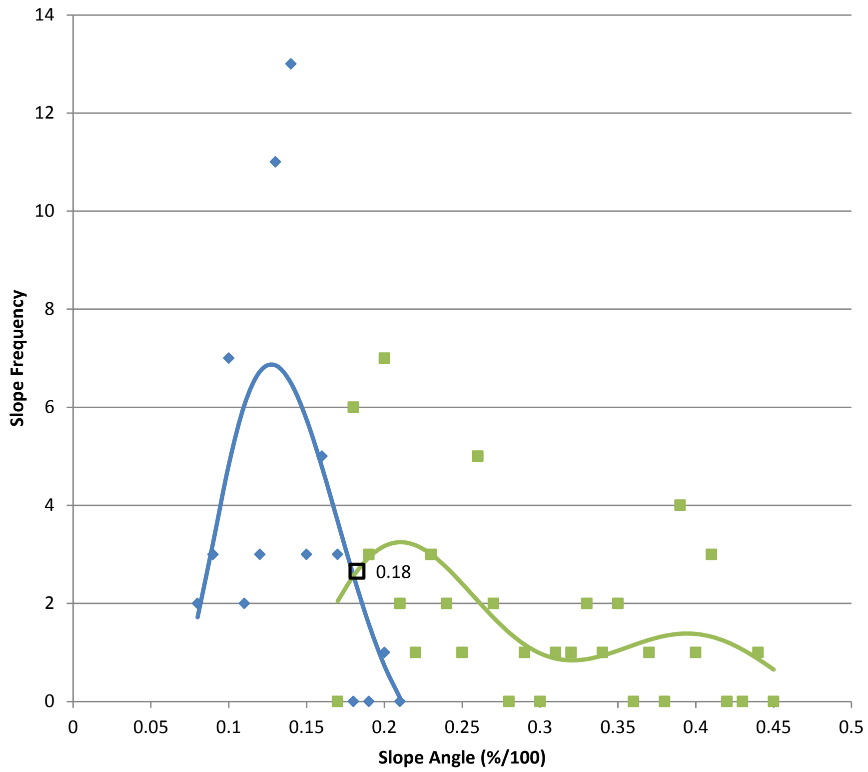


Figure 10-44: Siltstone Medium/Low Slope Distribution

10.12.3 Model Verification

Once the predictive model was established, the model was verified against the known observations for the Siltstone.

Two Bays Road

The slope in the vicinity of the Two Bays Road landslide is shown in Figure 9-45. The area in the immediate vicinity of the landslide is surrounded by a red line. The 0.5m contours of the slope have been included to aid in the visualisation of the slope. It can be seen from the contours that the steep slope continues consistently down slope (bottom right) and up slope (top left) from the area of the landslide. There is then a break in slope both up and down slope.

The results of the verification are shown in Figure 9-38 and are discussed below.

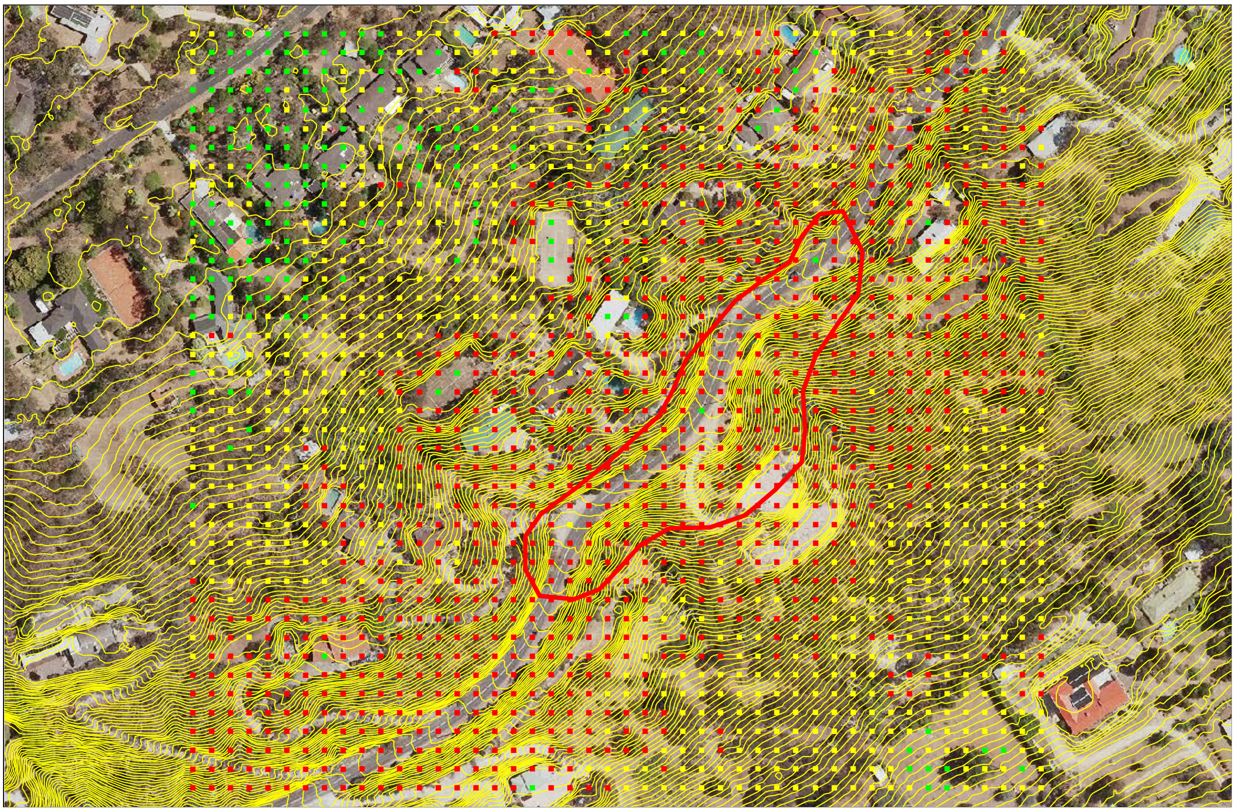


Figure 10-45: Two Bays Road - PA(1996)

At the break in slope, the model predicts a change to a moderate landslide susceptibility. Further up slope the slope flattens out and the model predicts a change to a low susceptibility. The model accurately reflects observed conditions.

Moorooduc Quarry

The area in the vicinity of the Moorooduc Quarry is shown in Figure 9-45. The perimeter of the quarry itself is surrounded by a red line. The 0.5m contours of the slope have again been included to aid in the visualisation of the slope. It can be seen from the contours that while the slopes within the quarry are extremely steep, a very steep escarpment runs from the south-west to the north-east. The escarpment is visible as tight contours running from the bottom-left to the top-right of the figure compare to the wider spaced contours in the top-left and bottom-right corners of the figure. This escarpment is the continuation of the escarpment at Two Bays Road.

The results of the verification are shown in Figure 9-38 and are discussed below.

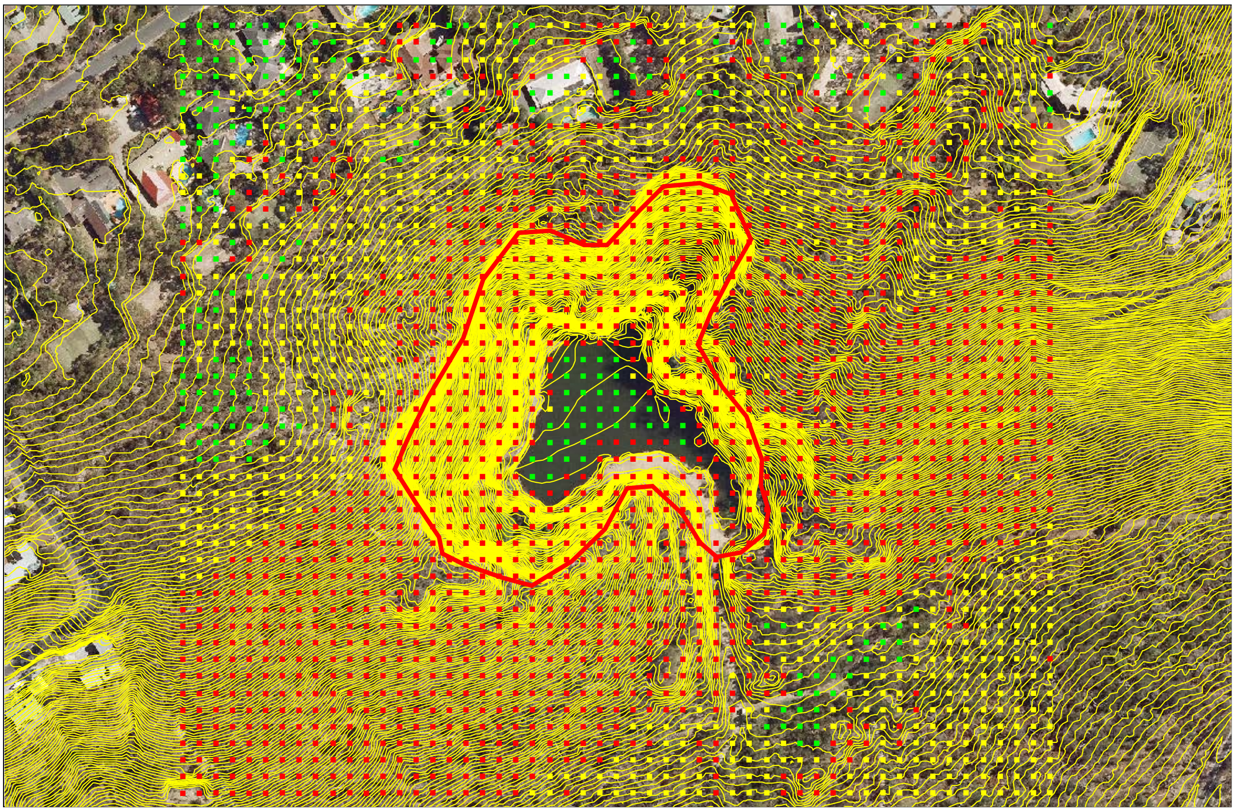


Figure 10-46: Moorooduc Quarry - PA(2000C)

The model predicts the position of the quarry and indicates there is potential for instability beyond the quarry for a distance of approximately 30m. The model also identifies the steep slopes to the east and west of the quarry that were also observed at Two Bays Road.

The inclinometer constructed up slope of the quarry on the north side indicates slow creep occurring. The model predicts a moderate landslide susceptibility in this area which is consistent with the presence of creep.

10.12.4 Final Model

The final model which was based on the statistical analysis of the landslides identified in various reports has adopted the low/medium susceptibility boundary as having a slope of 18% and the medium/high susceptibility boundary as having a slope of 36%.

The model was then verified by analysing the areas in the vicinity of several other areas of instability. The model was found to have a good correlation with the observed conditions.

Considering these values the susceptibility weighting for the Siltstone has been adopted as shown in Figure 9-47.

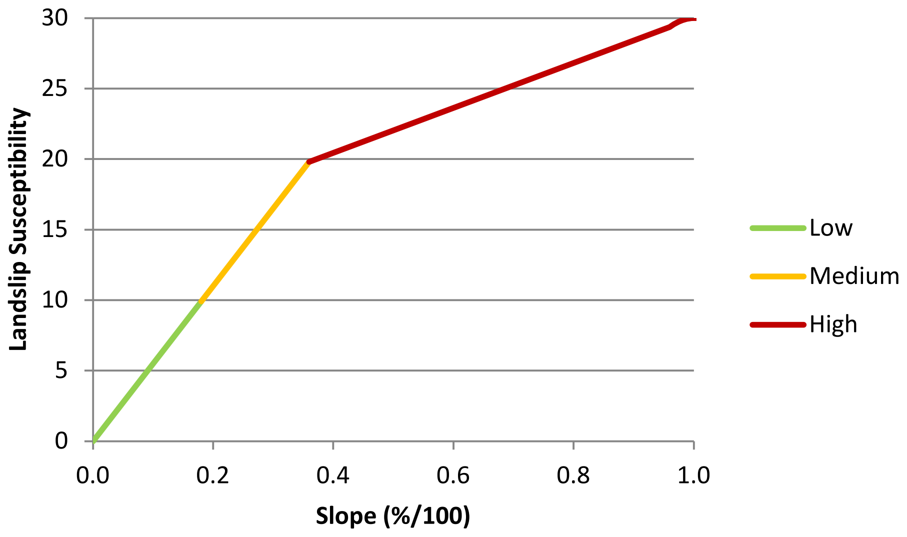


Figure 10-47: Slope vs. Susceptibility Weighting for Siltstone

11 RESULTS OF THE ANALYSIS

Once the relationship between geology, slope gradient and aspect had been developed and verified it was possible to conduct the analysis for the entire Mornington Peninsula Shire.

11.1 Data Analysis and Map Production

The analysis involved the determining the maximum slope and aspect of 6m radius circle and reviewing the geology for approximately 15.6 million locations across the Shire. This equates to approximately 50 days of full time computer time. At times, up to 6 personal computers were dedicated to the task.

The output of the analysis was a grid of susceptibility weighting values on an 8m x 8m grid across the Shire. The grid was separated into tiles of 500m x 500m to allow processing of the data more efficiently

In order to make the data visually accessible it was then necessary to convert the grid of data into smoothed polygons that defined the different areas of landslide susceptibility.

After discussions with Council it was decided that where individual points of one susceptibility value were surrounded by points of another susceptibility value the individual point would be ignored. This resulted in many small polygons being eliminated.

The polygons were produced by interpolating between the grid of susceptibility weighting values to identify “weighting contours” where the boundaries between low/medium and medium/high susceptibility would be located. Polygon tiles of 5km x 5km were produced from the 500m x 500m data tiles. The production of the susceptibility contours took approximately another 30 days of full time computer time.

A view of the output of the susceptibility analysis is shown in Figure 11-1.

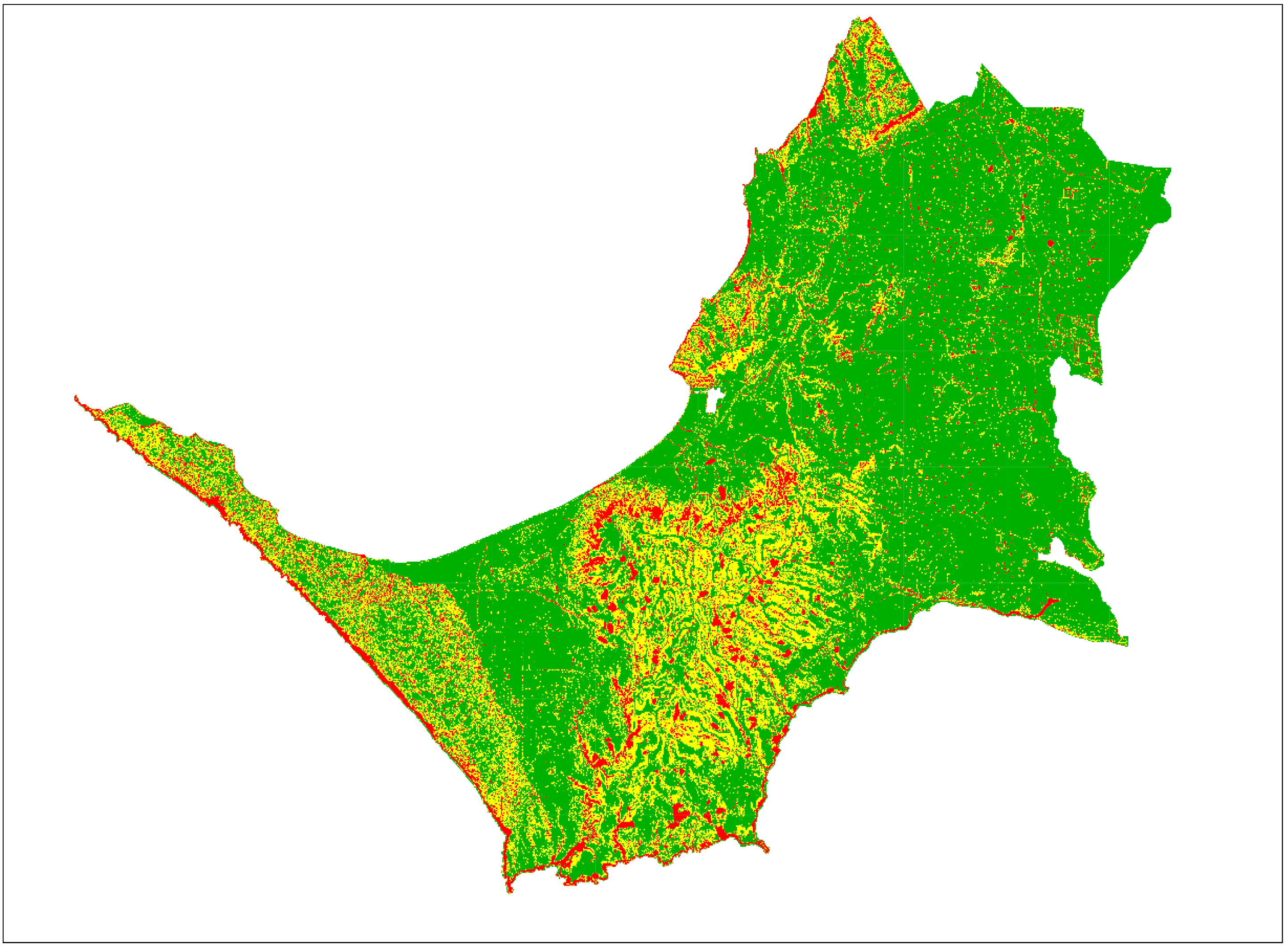


Figure 11-1: Slope Susceptibility Output

11.2 Areas Not Included

During a review of the analysis results it was observed that there was a significant variation and discrepancy between the analysis results, site contours and recent aerial photographs for the area in the vicinity of the recently developed Martha Cove site in Safety Beach. The discrepancy is attributed to ongoing earthworks that were occurring during the LIDAR acquisition time.

As the accuracy of the susceptibility analysis in this areas could not confidently be determined it was decided that this areas would be excluded from the study.

Future review of this area is recommended.

12 CONCLUSIONS

The purpose of this report is to provide an assessment of landslide susceptibility for the Mornington Peninsula Shire. The assessment is primarily a desk – top review of the available information using existing literature, available data, reports and aerial photography. Very little fieldwork has been carried out in this study although previous fieldwork studies by the writers and others have been used throughout the study.

This report is not an assessment of landslide hazard or landslide risk. Such assessments will still need to be carried out on an individual site basis using intrusive investigations and site specific field observations. This report is **not** a replacement for these investigations and is only a guide as to the expected landslide susceptibility

The assessment is specifically for the area within the Mornington Peninsula Shire and while there may be locations outside the Shire that have similar geologies, the findings of this assessment should not be used directly for assessment of areas outside the Shire without further assessment.

Furthermore the landslide susceptibility modelling is based primarily on the geology and the slopes, although other less important factors are also considered such as aspect. However, other important factors such as the depth to the groundwater, the presence of perched water table, vegetation and the depth to the rock were not able to be considered in this assessment and the assessment is based on typical conditions occurring in the study. Consequently if there is shallow bedrock in the area of landslip, the susceptibility assessment is likely to be conservative. Conversely, if there is a perched water table or shallow groundwater, the predicted landslip susceptibility zones may underestimate the landslip susceptibility. It is also recognised that vegetation and development will impact the landslip susceptibility in an area, but this was not included in the model due to the lack of field data to model the impacts. As such variation can be expected and there may be sites which are more susceptible to landslide than predicted while there also may be sites which are less susceptible to landslide than predicted. It is therefore essential that findings of this assessment be followed up with an appropriately detailed geotechnical investigation on a site by site basis in order to appropriately assess each site.

The reader attention is drawn to the accuracy of any boundaries between low, medium and high landslip susceptibility. As discussed in these reports, the reader should be careful in using ‘lines’ to define the edge of any susceptibility areas. Issues such as slope anomalies, statistical variations in the boundaries, inaccuracy in the determination of geological boundaries and unusual ground conditions may and will impact the boundaries of the landslip susceptibility zonation. The degree of inaccuracy of any landslip susceptibility zonation will depend on a number of factors and needs to be assessed on an individual site basis.

The GIS assessment of the landslide susceptibility is based on the slope gradient, aspect and local geology as well as numerous geotechnical reports conducted across the Shire. The accuracy of any GIS based system is limited to the accuracy of the least most accurate data used in the analysis. In the case of this assessment, that is the geology maps which are based on a 1:63,360 scale. While the maps produced in this assessment may be ‘zoomed in’ to a finer scale, details observed at the finer scale are still dependant on the accuracy of the 1:63,360 geology maps and variation can be expected. In many areas, the accuracy of the geological maps will be of the order of 100m

The assessment provides a rating for how susceptible a particular location is to landslides. It does not predict how a landslide at one location may affect another location. Therefore, this assessment does not include areas that may be affected by landslide run-out or landslide regression.

On areas of ‘high landslip susceptibility’, a landslip risk assessment is essential to consider risk to property and life for the proposed development and also consider the impacts on nearby properties. The Council has adopted the practical approach that provided a development above or below an existing property does not increase the risk to property or life of the neighbouring property, the developer is not required to address this risk to the neighbour's property. The developer is required to address the risk to property and life for the new development.

This study does not obviate or reduce the need for a geotechnical investigation for a proposed development or building on an existing property. Any appropriately undertaken geotechnical investigation undertaken by an experienced geotechnical engineer or geologist for a particular property **should override this study**. The purpose of this study is not to reduce the need for geotechnical investigation, analysis and assessment but to provide guidance to the Council on the extent and detail of a geotechnical investigation required. Previously residents have complained that the extent of geotechnical investigation was inconsistent and ad hoc and this study will provide the Council with appropriate method to recommend and insist on an appropriately level of investigation using a rigorous and impartial study

This study is not to prevent or restrict development in an area of 'high' landslip susceptibility provided it is appropriately designed. However there are some areas where development is not advisable. While in these areas, the owners may be prepared to accept a higher risk than 'tolerable', the Council has previously adopted the 'tolerable' risk as the maximum risk that the Council will permit. There are a number of dwellings in areas of 'high' susceptibility that have existing with satisfactory performance for many years, possibly in part due to the reasons discussed in this report and unpredictability of when ground movements may occur.

Details of the required level of investigation for each landslide susceptibility category are provided in this report. However, as part of any geotechnical investigation, whether for a low susceptibility site or a high susceptibility site, the geotechnical practitioner assessing the site should always be cognisant of the potential for landslide stability issues.

13 RECOMMENDATIONS FOR FURTHER WORK

The GIS has the ability to be upgraded as further geotechnical studies or other literature becomes available. It is recommended that the Council update the study in 5 – 10 years' time to include the new reports as they become available and re-run the GIS which will include the new information.

14 ACKNOWLEDGEMENTS

This study has been conducted over a number of years and the writers wish to acknowledge the input of other experts, namely:

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- Ken Toleman, Geocomp Consulting

The writers also wish to acknowledge the support and input of John Ault Connell, Roz Franklin, John Annear and Terry Boyd, officers of the Mornington Peninsula Shire Council.

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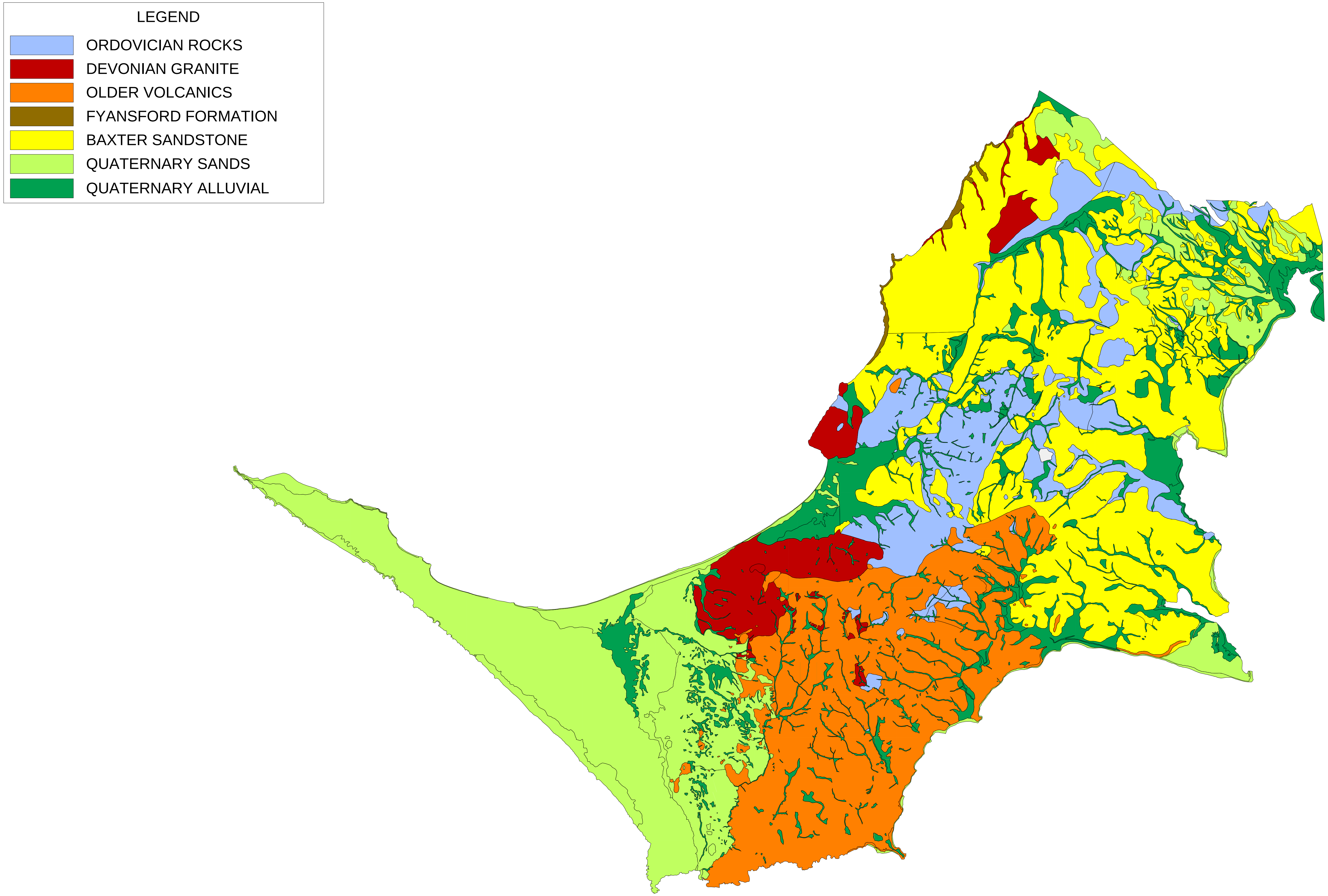
Appendix A
1 Page

Geological Map



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PROJECT:
LANDSLIDE SUSCEPTIBILITY ASSESSMENT, STAGE 2
MORNINGTON PENINSULA SHIRE, VICTORIA

SCALE (A3): 1:200,000	DATE: 30 JAN 2012	TITLE: GEOLOGY MAP	
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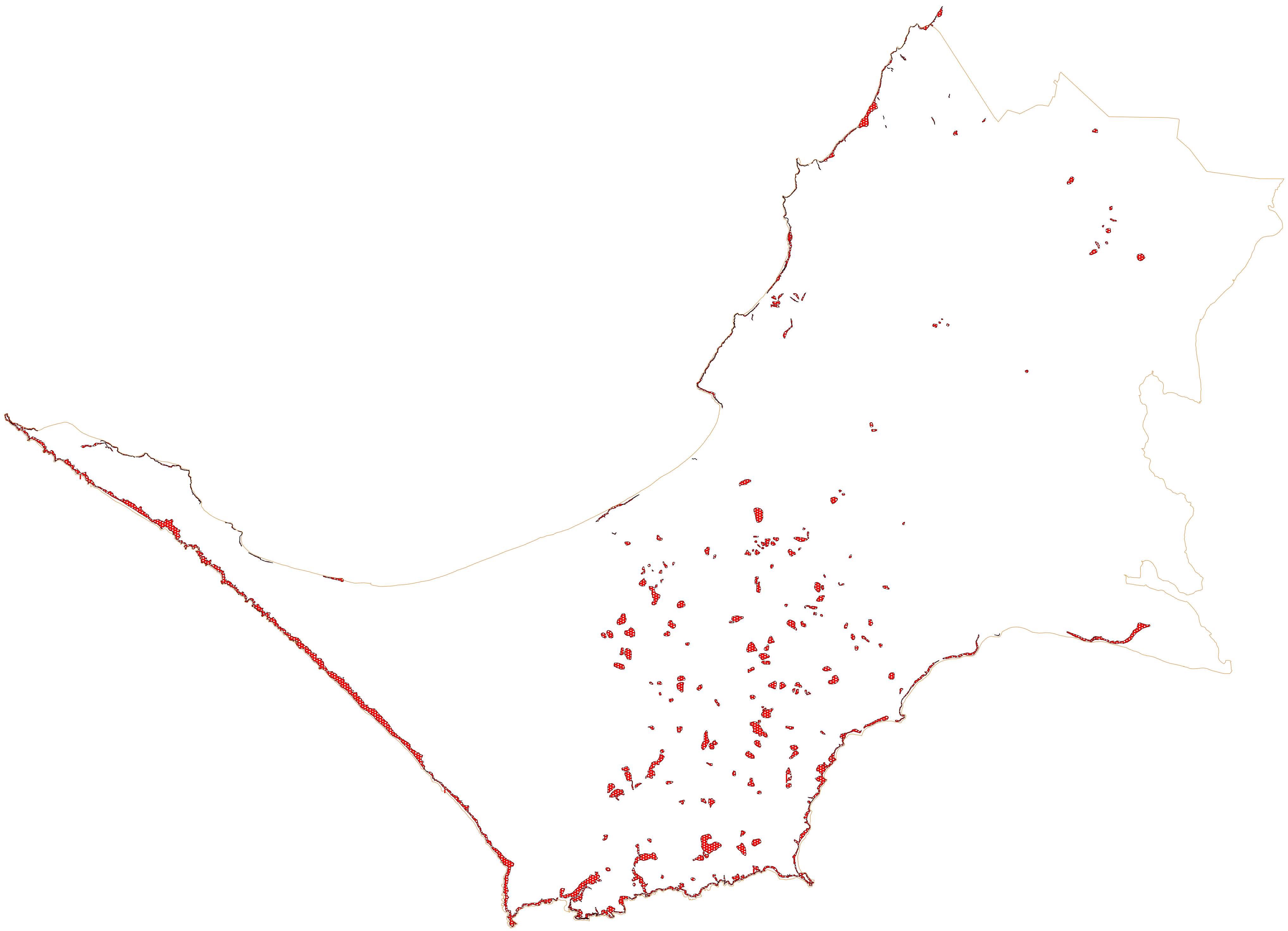
Appendix B
1 Page

Identified Slope Failures



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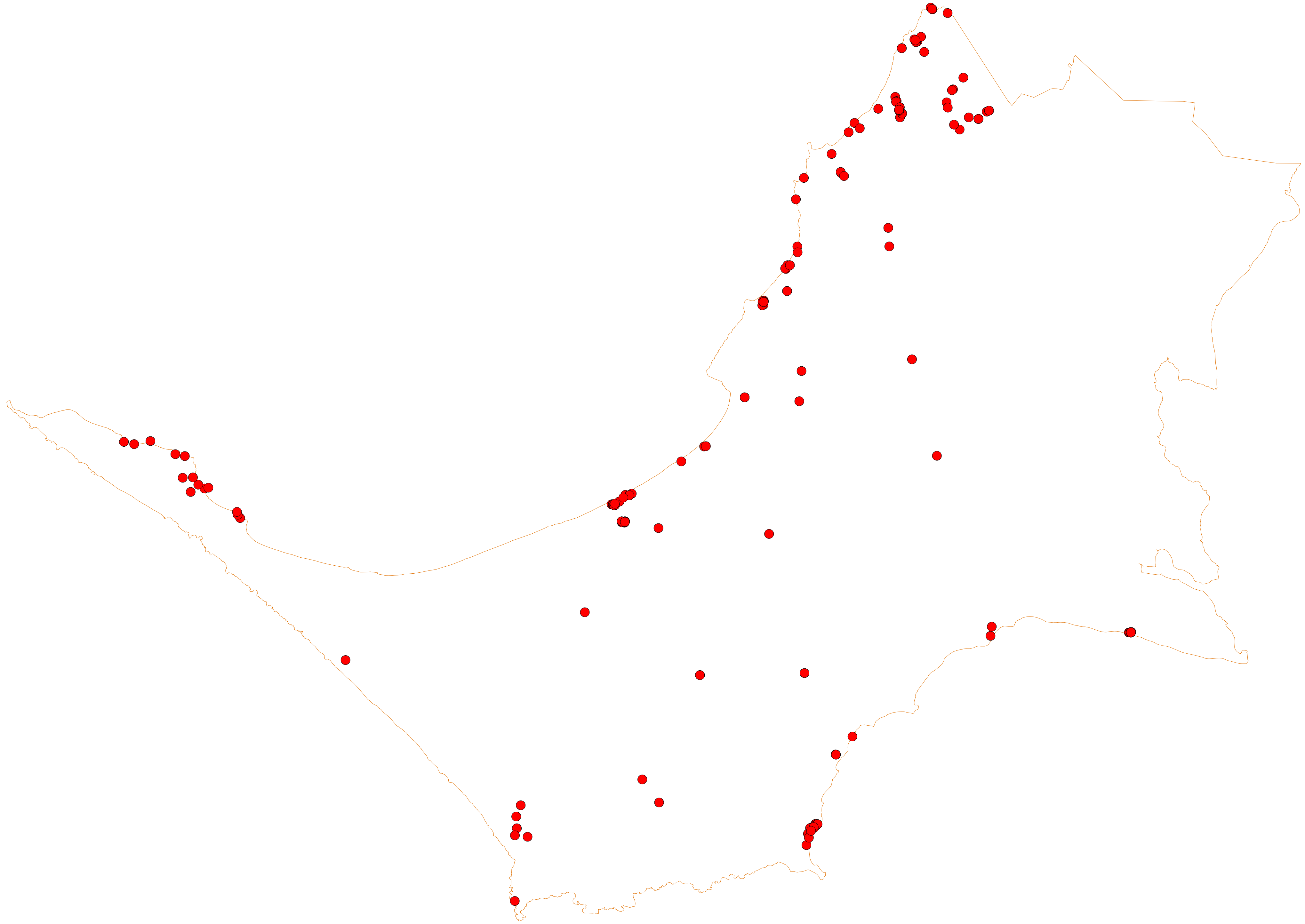
		DRAWN:	DBS	JOB NO.:	207166		
Cardno Lane Piper Pty Ltd www.lanepiper.com.au ACN 120 109 935 www.cardno.com.au		FILE REF:	207166-Landslide.WOR			REV NO.: 0	FIG NO.: 1

Appendix C

1 Page

Previous Consultants Reports



Cardno LanePiper Cardno Lane Piper Pty Ltd www.lanepiper.com.au ACN 120 109 935 www.cardno.com.au	PROJECT: LANDSLIDE SUSCEPTIBILITY ASSESSMENT, STAGE 2 MORNINGTON PENINSULA SHIRE, VICTORIA	SCALE (A3): 1:200,000	DATE: 30 JAN 2012	TITLE: PREVIOUS CONSULTANTS REPORTS	
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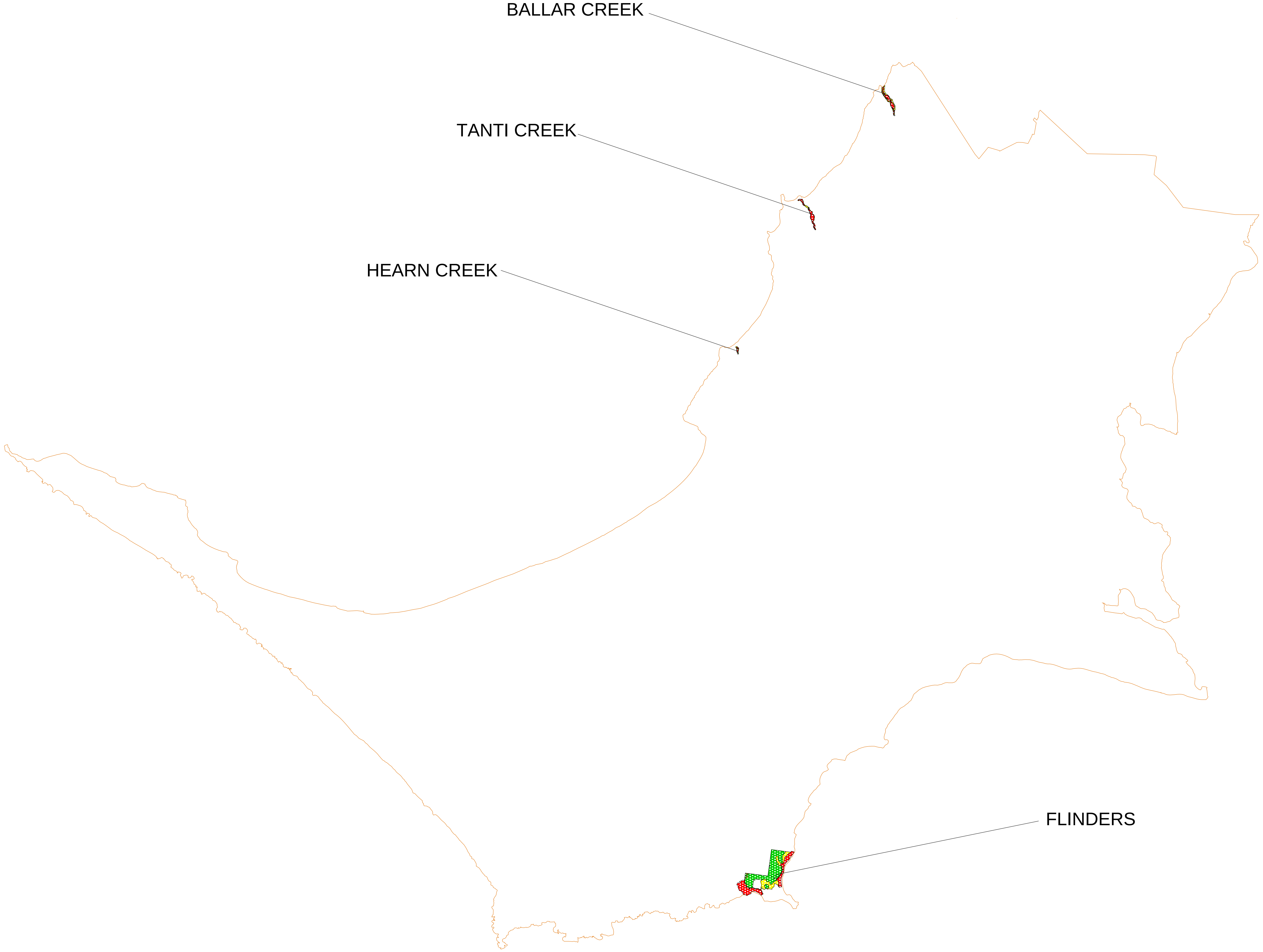
Appendix D
1 Page

Previous Landslide Susceptibility Studies



Cardno LanePiper Cardno Lane Piper Pty Ltd ACN 120 109 935 www.lanepiper.com.au www.cardno.com.au	PROJECT: LANDSLIDE SUSCEPTIBILITY ASSESSMENT, STAGE 2 MORNINGTON PENINSULA SHIRE, VICTORIA	SCALE (A3): 1:200,000 DRAWN: DBS	DATE: 30 JAN 2012 JOB NO.: 207166	TITLE: PREVIOUS SUSCEPTIBILITY STUDIES
		FILE REF: 207166-Studies.WOR		REV NO.: 0 / FIG NO.: 1

Appendix E
1 Page

10m Contours

Cardno LanePiper Cardno Lane Piper Pty Ltd www.lanepiper.com.au ACN 120 109 935 www.cardno.com.au	PROJECT: LANDSLIDE SUSCEPTIBILITY ASSESSMENT, STAGE 2 MORNINGTON PENINSULA SHIRE, VICTORIA	SCALE (A3): 1:200,000	DATE: 30 JAN 2012	TITLE: 10m CONTOUR MAP	
		DRAWN: DBS	JOB NO.: 207166		
		FILE REF: 207166-Contours.WOR		REV NO.: 0	FIG NO.: 1

Appendix F

1 Page

About Geotechnical Reports

LIMITATIONS OF GEOTECHNICAL & ENVIRONMENTAL REPORTS

The purpose of this report is to provide a geotechnical and contamination assessment of the sites examined. The information provided herein will reduce the exposure to risks, but no assessment can eliminate them. Nonetheless, even a rigorous assessment may fail to detect all of the geotechnical or contamination conditions on a site. Site variations may have occurred in areas not investigated or sampled.

This report should not be used when the nature of the proposed site usage changes, when the size, layout, or location of the development is modified, when the site ownership changes nor should it be applied to a nearby area.

The site geotechnical and contamination assessment identifies actual subsurface conditions where the samples were taken and when they were taken. The contamination tests are carried out by an external NATA accredited chemical laboratory and any liability with regards to the testing is solely this laboratory's responsibility. The laboratory results together with the field, and other data were then interpreted by geotechnical and environmental engineers who rendered an opinion about the overall subsurface conditions, the nature, mobility, type and extent of contamination, its likely impact on the proposed development with a discussion of the remediation measures considered likely.

The actual conditions may differ from the inferred conditions, as no person (no matter how qualified) or even the most detailed subsurface investigation can predict with confidence what may be hidden by soil or water or may have altered with time. Often the interface between contamination zones may be more abrupt or gradual than anticipated. The actual conditions in an area may differ from that predicted. Site assessments are limited by time and may be affected by natural processes such as erosion, mankind altering the ground conditions, or chemical reactions of potential contaminants altering the physical characteristics of the soil or water on the site.

Costly problems can occur if the report is misinterpreted. To avoid these problems, Cardno Lane Piper Pty Ltd should be retained to work with the appropriate design professionals and to review the adequacy of their plans and specifications relative to the geotechnical matters. No person other than the client should apply the report without first conferring with Cardno Lane Piper Pty Ltd.

This report should only be reproduced in its entirety. Reproduction of borehole or testpit logs alone without the entire report should not be permitted. Redrafting of the borehole or testpits logs for inclusion in drawings or other reports should not be allowed as errors in the drafting can occur. It is recommended that the report be made available in entirety to persons and organisations involved in the project such as contractors. Simply disclaiming responsibility for the accuracy of the subsurface or geotechnical information does not insulate the organisation from liability. The more information a contractor has available to him, the better able he is to avoid costly construction problems and costly adversarial situations.

Finally, geotechnical and environmental reports are based extensively on opinion and judgment and are less exact than other sciences. The report may contain a number of explanatory clauses or limitations on the results to inform the client about the restrictions of the report. These clauses are not meant to be exculpatory clauses to foist liability onto another person, but to identify where Cardno Lane Piper's and the client's responsibilities start and finish. Their use is to clarify where individual responsibilities lie and to allow the individual to take appropriate actions.