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Geohazard mitigation in remote and rugged terrain

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Abstract

Newmont Asia Pacific Region (APAC) operated a number of exploration tenements in Papua New Guinea, the Solomon Islands and Indonesia. A common feature to all these sites were rugged terrain, very thick vegetation canopy, high intensity rainfall and relatively young geology. Geohazards such as landslides, earthquakes and flash flooding are common in these terrains. Past incidents at the exploration sites highlighted the requirement for geotechnical input prior to site selection. This article explains the process that was developed in the preparation of a Geohazard Mitigation Tool (GHMT) that was used for the selection of safe sites suitable for Newmont exploration infrastructure. Available good quality topographic images were used to acquire slope, drainage and landslide information. Regional and local soils and geology maps were helpful in ascertaining soils conditions. Prevailing wind information was also useful. To put all the above information together into a geohazard rated map of the exploration regions, ArcGIS tools were utilised.

1 Introduction

Newmont APAC carried out exploration activities in Papua New Guinea (PNG), Solomon Islands and Indonesia. Most of these sites were located in remote, extremely rugged and heavily vegetated tropical terrains with high rainfall intensities. These areas are young and active in geological terms and geohazards like landslides, earthquakes and flash flooding are common. To be aware of such geohazards is important when operating in these regions to maintain worker safety. Lessons learnt from serious incidents within the exploration industry in these regions highlighted the need to pay attention to the earthworks and construction practices.

The exploration activities involved in setting up infrastructure such as exploration camps, drill pads, helicopter pads (helipads), storage facilities, access and supply tracks. The expected service lives of these infrastructures in general were relatively short. These activities should ideally be situated in stable areas but due to the ruggedness of the terrain, sourcing such sites was difficult, and when such a site was selected a certain amount of ground disturbance was unavoidable in order to establish the infrastructure required. The key to good hillside practices as defined in Australian Geoguide LR8 (Australian Geomechanics Society, 2007b) is to minimise ground disturbance in accommodating infrastructure.

With the thick vegetation cover, canopy and the undergrowth, it was very difficult to ascertain true ground conditions in the field. Prior to introduction of the GHMT, in order to select suitable sites Newmont exploration teams had to resort to considerable amount of vegetation clearance in order to access and check the suitability of the selected sites. Due to unfavourable geotechnical conditions certain cleared sites had to be abandoned when found not fit for the purpose. This was time consuming and involved unnecessary clearing of vegetation and delays in obtaining approvals for land clearing. In order to improve the site selection process the author developed a desk study approach as a first step towards selecting relatively safe sites for intended infrastructure, without having to disturb virgin land unnecessarily.

Certain geohazards were inherent in the Newmont exploration areas due to the ruggedness of the terrain, the proximity to tectonic plate boundaries and being in the tropics with high intensity rainfall. Types of geohazards in the Newmont exploration environment were landslides, earthquakes and flash flooding.

It was important to make the exploration personnel aware of the geohazards for safe operation. For this purpose a targeted training package was formulated for exploration field personnel.

2 Literature review

2.1 Geohazard mapping

A natural hazard is defined (Varnes, 1984) as the "*probability of occurrence within a specified period of time and within a given area of a potentially damaging phenomenon*". According to Bell (2006), geohazards are not all natural and some can be influenced by or brought about by man. Geohazards like landslides, earthquakes and flash floods can cause widespread destructions and impose constraints on development. Therefore it is important that the geohazards are understood in order that their occurrences and behaviours can be predicted and measures could be taken to reduce their impact.

Early work on landslide hazard mapping was done by Varnes (1984) and Hansen (1984). Cruden and Varnes (1996) further modified the landslide classification system. Van Westen et al. (2005) looked at multi-hazard landslide risk assessment with various components contributing to landslides.

Use of landslide zoning maps for managing the risks have been recently documented by Fell et al. (2005), (2008), Cascini et al. (2005), and Australian Geomechanics Society (2007a). Van Westen et al. (2008) looked into the main layers necessary for landslide susceptibility, hazard and risk assessment. These can be subdivided into landslide inventory, environmental factors, triggering factors and elements at risk.

Remote sensing data can be the main source of information for landslide inventories, Digital Elevation Models (DEM) and land use maps (Soeters and Van Westen, 1996; Metternich et al., 2005; and SafeLand, 2010).

According to Horton et al. (2008) run out assessment is seldom performed except for very large events, due to the low resolution of regional scale analyses. Hungr et al. (2005) looked into empirical and analytical methods for assessing landslide runout. For hazard zoning purposes both methods are widely used given their capability of being integrated in GIS platforms (SafeLand, 2011). Thorough analysis of the landslide hazards requires laboratory test of materials, test borings, geophysical prospecting and numerical modelling analyses of potential failure surfaces (Kim and Kim, 1991).

Kim et al. (1992) prepared a regional Geohazard map for Seoul metropolitan area using GIS to incorporate the elements of topography, geology and soil along with ground water, rainfall and vegetation. This was aimed at predicting landslide hazard potential.

Saha et al. (2002) in their GIS based Geohazard zonation introduced buffer zones around the landslides and drainage systems.

2.2 Good hillside construction practices

A useful set of guidelines on good hillside construction practices were listed by Walker et al. (1985) and Australian Geomechanics Society (2000). They recommended:

- Retaining natural vegetation where possible and avoid indiscriminately clearing the site.
- Retain natural contours where possible and avoid indiscriminate bulk earthworks.
- Earthworks cuts: do's and do not's:
  - Do – minimise cut depths.
  - Do – support with engineered retaining walls or batter to appropriate slope.
  - Do – provide drainage measures and erosion control.
  - Do not – make large scale cuts and benching.
  - Do not – make unsupported cuts.
  - Do not – ignore drainage requirements.

- Earthworks fill: do's and do not's:
    - Do – minimise fill height.
    - Do – strip vegetation and topsoil and key into natural slopes prior to filling.
    - Do – use clean fill materials and compact to engineering standards.
    - Do – batter to appropriate slope or support with engineered retaining wall.
    - Do – provide surface drainage and appropriate subsurface drainage.
    - Do not – place loose or poorly compacted fill.
    - Do not – block natural drainage lines.
    - Do not – fill over existing vegetation and topsoil.
    - Do not – include stumps, trees, vegetation, topsoil, boulders, building rubble, etc. in fill.

3 Geotechnical support for exploration projects

In the early stages of Newmont exploration camp sites in PNG, very little geotechnical input had gone into site selection and earth works. An incident involving multiple fatalities occurred at another exploration property in PNG operated by another company and some incidents occurred at a Newmont exploration site in PNG all of which highlighted the requirement to place more rigour into site selection and construction practices.

Incident investigations revealed that site selection and construction work require:

- Increasing the geohazard awareness of the site personnel.
- Adaptation of good hill side practices during construction.
- Systems to maintain minimum standards on:
    - Site selection for infrastructure (drill sites, helicopter pads, camp sites, access tracks).
    - Good earth works practices (cut and fill, surface drainage).
    - Good construction practices (camp construction, retaining wall construction).
    - Rain affected ground stability.
    - Post disturbance ground monitoring.

The aims of the geotechnical support to the exploration teams were to:

- Enhance awareness of site exploration staff on geohazards including hazard identification methods.
- Set up geotechnical standards and procedures.
- Empower the site exploration staff to conduct site selection processes.
- Geotechnical assessment of the selected sites.

The author provided geohazard awareness training to Newmont exploration field staff in different regions, covering both the theory and practice of mapping geohazards. Exploration field personnel who had undergone geohazard awareness training were designated as a Geohazard Awareness Trained Person (GTP) and were empowered to carry out geotechnical site assessments. This training makes them competent to:

- Measure slope angles using clinometers.
- Recognise basic slope forms (e.g. straight, convex, concave and undulating S-shaped).
- Recognise slope instability features.

- Familiar with geomorphological mapping symbols.
- Make a sketch of a site and a section using standard morphological mapping symbols.
- Able to populate a standard template.

The paperwork on the geotechnical site assessments carried out by GTP gets reviewed by a competent geotechnical engineer before the site work progresses to the next stage.

4 Selecting safe sites for exploration infrastructure

Early stages of exploration and site selection for exploration infrastructure were governed basically by the exploration targets. Newmont exploration teams were purely relying on the field observation by the exploration geologists and the field staff to select suitable sites. Newmont exploration management later sought assistance from the author to set up a geotechnical process in site selection. This has lead to the establishment of a set of tools and procedures to select safe sites for exploration infrastructure. The author after teaming up with the Remote Sensing Specialist and a GIS specialist formulated the GHMT. Due to the dense vegetation, both thick canopy and the thick undergrowth in the region, it was extremely difficult to get an appreciation of the topography without clearing land. In some cases the cleared land had to be abandoned when found to be geotechnically unsound during the site geotechnical assessment. This unnecessary clearing of land had caused financial and environmental constrains and contributed to land degradation.

The system adopted by Newmont exploration site selection process consisted of three stages:

1. Construction of GHMT for each exploration lease. The GHMT is a geohazard rated map for each exploration lease, prepared with remote sensing, GIS and geotechnical input. It provides guidance to the site exploration geologists to enable exploration infrastructure to be preferentially located in areas with relatively low geohazards. In remote exploration environments it is not practical to establish and maintain sophisticated geotechnical controls to ensure the safety of the infrastructure sites. Areas with higher geohazard risks require establishment of such geotechnical controls. Therefore, it is prudent to initially select areas with low geohazards.
2. Locate the required exploration infrastructure sites inside the low geohazard zones using GHMT followed by field geotechnical inspection to check the site suitability prior to site clearance by a GTP. If the pre-clearing assessment indicated the site to be geotechnically favourable, it progressed to the site clearing stage. At each stage of inspection a GTP populated the template (Table 1) along with a site plan and a representative section. This work gets reviewed by a geotechnical engineer. The geotechnical engineer advises the site personnel on earthworks and surface drainage controls.
3. If the site geotechnical assessment indicated moderate or high geohazard rating, the site was abandoned. At this stage the geotechnical engineer inspected the site to either recommend geotechnical controls in order to progress to the next stage or to abandon the site.

Table 1 Template used in site geotechnical assessment

<table>
<tr><td>Initial Geohazard Rating (from GHMT)</td><td colspan="2"></td><td colspan="2">Final Risk Rating After Completion of This Form</td><td></td></tr>
<tr><td>Feature (e.g. drill pad, camp, etc.)</td><td>Reconnaissance (by air)</td><td>Pre-clearing (on ground)</td><td colspan="2">Post-clearing (on ground)</td><td>Note: May select more than one item in lists/boxes below</td></tr>
<tr><td colspan="5">Terrain
Main Slope: Flat 8(0–1°) Gentle (1–5°) Moderate (5–17°) Steep (17–35°) Very Steep (>35°)
Side Slopes: Flat (0–1°) Gentle (1–5°) Moderate (5–17°) Steep (17–35°) Very Steep (>35°)</td><td>Vegetation
Forest: Mature, young, dense scrub, grassland, garden</td></tr>
<tr><td colspan="6">Shape: Main Slope Planar Undulating Strongly Undulating Concave Convex
Side Slopes Planar Undulating Strongly Undulating Concave Convex</td></tr>
<tr><td colspan="6">Drainage: Depressions Swampy Stream Channel Gully Springs Well drained (show on Plan)</td></tr>
<tr><td colspan="6">Site Risk Assessment: (Show on plan sketches)</td></tr>
<tr><td colspan="2">1. Steep concave slope above/below site</td><td></td><td colspan="2">13. Bulging of ground</td><td></td></tr>
<tr><td colspan="2">2. Steep convex slope above/below site</td><td></td><td colspan="2">14. Hummocky ground present</td><td></td></tr>
<tr><td colspan="2">3. Cracks 90° to ridge</td><td></td><td colspan="2">15. Swampy ground</td><td></td></tr>
<tr><td colspan="2">4. Site located on steep to very steep slope</td><td></td><td colspan="2">16. Close to streams/gullies</td><td></td></tr>
<tr><td colspan="2">5. Evidence of past landslide</td><td></td><td colspan="2">17. Back tilted slopes</td><td></td></tr>
<tr><td colspan="2">6. Back scarp present</td><td></td><td colspan="2">18. Ridge is narrow</td><td></td></tr>
<tr><td colspan="2">7. High rock face fractured loose</td><td></td><td colspan="2">19. Previous recent land clearing (other than for site clearance)</td><td></td></tr>
<tr><td colspan="2">8. Steep cut >3 m required</td><td></td><td colspan="2">20. Trees tilted or bent</td><td></td></tr>
<tr><td colspan="2">9. Cracks parallel to ridge</td><td></td><td colspan="2">21. Seeps or springs present</td><td></td></tr>
<tr><td colspan="2">10. Scree slopes above</td><td></td><td colspan="2">22. Close to assets (houses, road, power poles, buildings etc.)</td><td></td></tr>
<tr><td colspan="2">11. Creek bank erosion below</td><td></td><td colspan="2">23. Possible to be flooded (site is at least 10 m above stream base*)</td><td></td></tr>
<tr><td colspan="2">12. Subsidence of ground</td><td></td><td colspan="2">24. Other (Structures will not need to be built on fill material)</td><td></td></tr>
<tr><td colspan="6">If selected one or more of items 1–10 then URGENT geotechnical engineer assessment is required</td></tr>
<tr><td colspan="6">Recommendations and comments:</td></tr>
</table>

5 GHMT construction

The GHMT is a geohazard rated map of the project area prepared with high definition remote sensing images and GIS and geotechnical assessment to provide guidance to the site exploration geologists. Newmont remote sensing specialist sources the suitable images of the exploration leases as requested by the geotechnical engineer. The primary input is topography sourced from available images (topography contour or GeoSAR or equivalent). Best topographic definition of rugged terrain with thick vegetation canopy can be obtained with LiDAR images, where larger wavelength radar which penetrates the tree canopy and reflects off the ground, is employed for image capture. Higher definition topographic images (smaller pixel sizes) provide accurate information that assists construction of the GHMT. Largest pixel size useful for in these analyses is 5 × 5 m. anything larger would not be suitable or useful for exploration infrastructure siting. Topographic images can be utilised for mapping landslides, measuring slope angles and slope aspects and for obtaining river systems information. Area inside the landslide boundary is considered as high geohazard rated area. Area downstream (DS) from the landslide within the area perceived to be the likely runoff zone and on the upstream (US) and the flanks of the landslide which the landslide is likely to propagate (conservative estimates based on the local experience) is also a high geohazard area. The hazard rating reduces progressively by moving away from the latter zones. The thickness of the zones away from the high to moderate geohazard is also conservative estimates based on the local experience. These bordering zones can be defined as buffer zones. Similarly buffer zones can also be established alongside the river systems. The river itself is considered hazardous under flood conditions. The impact of the flooding reduces with increasing elevation from the stream level. These elevation buffer intervals or zones (vertically and laterally (LAT)) can be estimated based on the local experience from high at the river level to low away from the river level.

The images of the project area are first converted into DEM using MIPS software (Figure 1), and are compatible with the GIS format to be used for further analysis. If the images are dated, they can be updated with new information, particularly information on new landslide locations provided by the site exploration geologists.

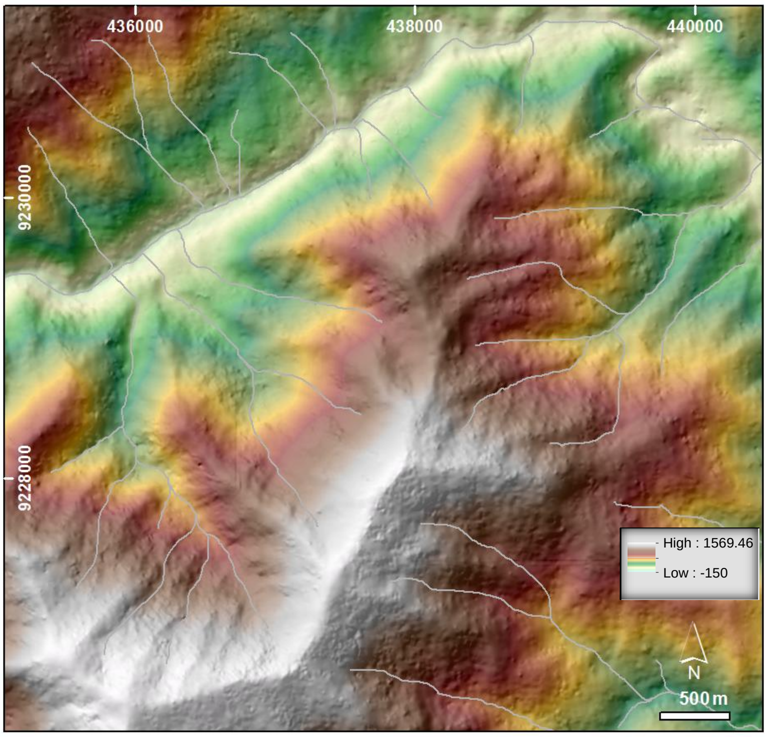

Figure 1 DEM (e.g. Gumots, PNG)

The GIS specialist would then use the DEM image to measure and digitise the following parameters using ArcGIS software:

- Slope angle
- Slope aspect
- Drainage
- Ridge spur
- Landslide
- Lithology

5.1 Slope analysis (S)

Slope analysis assigns a slope angle to each pixel. Based on the analysis, each pixel is classified according to five rating scales The lowest risk rating being the lowest number in the sequence 1 (i.e. flat slopes with slope angle varies from 0 to 1) and slopes greater than 35 being very steep and thus having the highest geohazard rating of 5 as shown in Table 2.

Table 2 Geohazard rating from slope angles

Geohazard Rating	Slope Angle	Classification
1	0–1°	Flat
2	1–5°	Gentle
3	5–17°	Moderate
4	17–35°	Steep
5	>35°	Very steep

Slope angle information is very significant in the geohazard analysis and was given a number 1 ranking and a weighting of 3 in the raster (gridded image) compilation. An example of slope analysis results are shown in Figure 2.

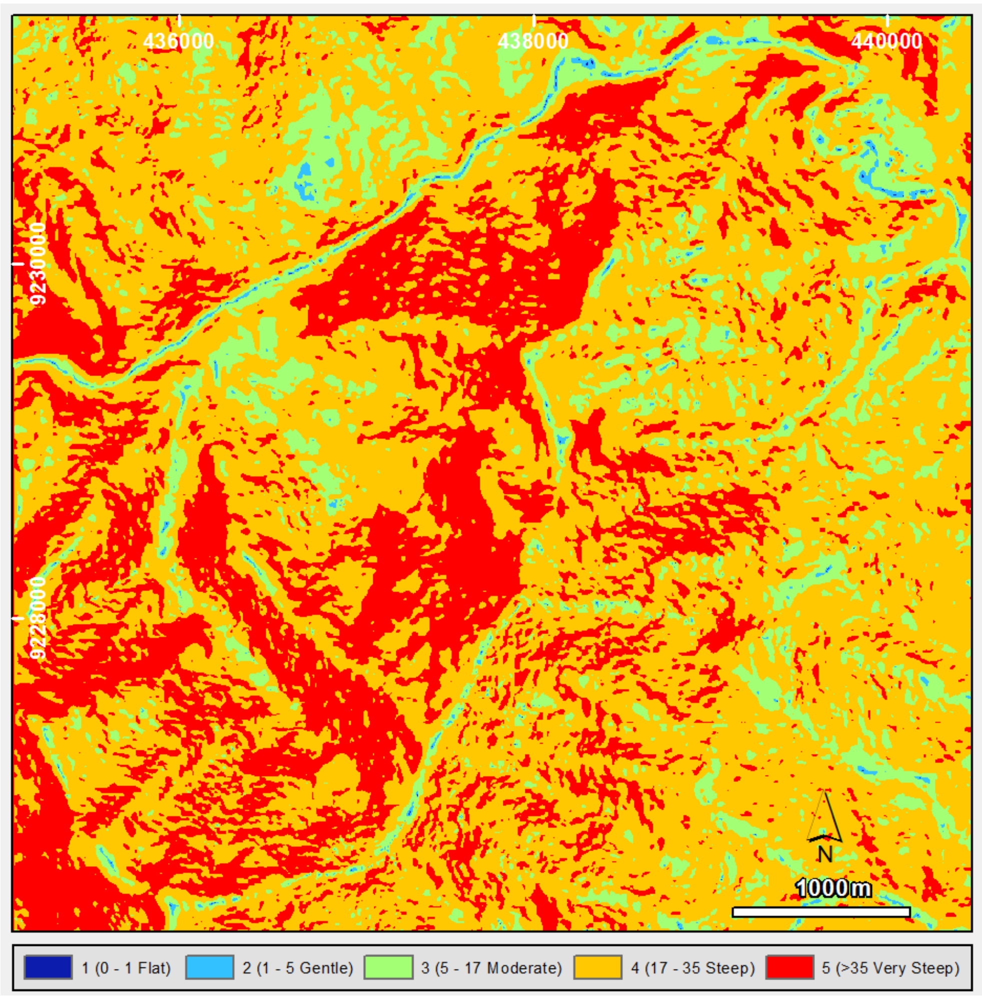

Figure 2 Slope analysis results (e.g. Gumots, PNG)

5.2 Slope aspect (A)

Slope aspect is the azimuth of a slope face and is derived from a DEM raster image. In general, prevailing winds (PW) bring rain; therefore, slopes facing PW get 'wetter' than other slopes and therefore have a higher likelihood of landslides, given all other conditions are the same (such as similar soil condition). This condition can be verified with field exploration geologists or personnel with local experience and it also coincides with the author's experience in this region, that slopes facing the prevailing wind direction would be expected to have higher incidents of landslides. In the GHMT the highest number in the sequence represents a high likelihood of landslide hazards as shown in Table 3 and Figure 3. A Slope aspect is given a lower ranking of 3 with a weighting factor of 1 to reflect the relative lesser importance and is presented in Figures 3 and 4.

Table 3 Landslide hazard ratings based on slope aspect

Slope Aspect	Rain Possibility	Likelihood of Landslide Hazard
Southeast quadrant	Not much rain impact	1
Northeast quadrant	Little rain impact	2
Southeast quadrant	Some rain impact	3
Northwest quadrant	Most rain impact	4

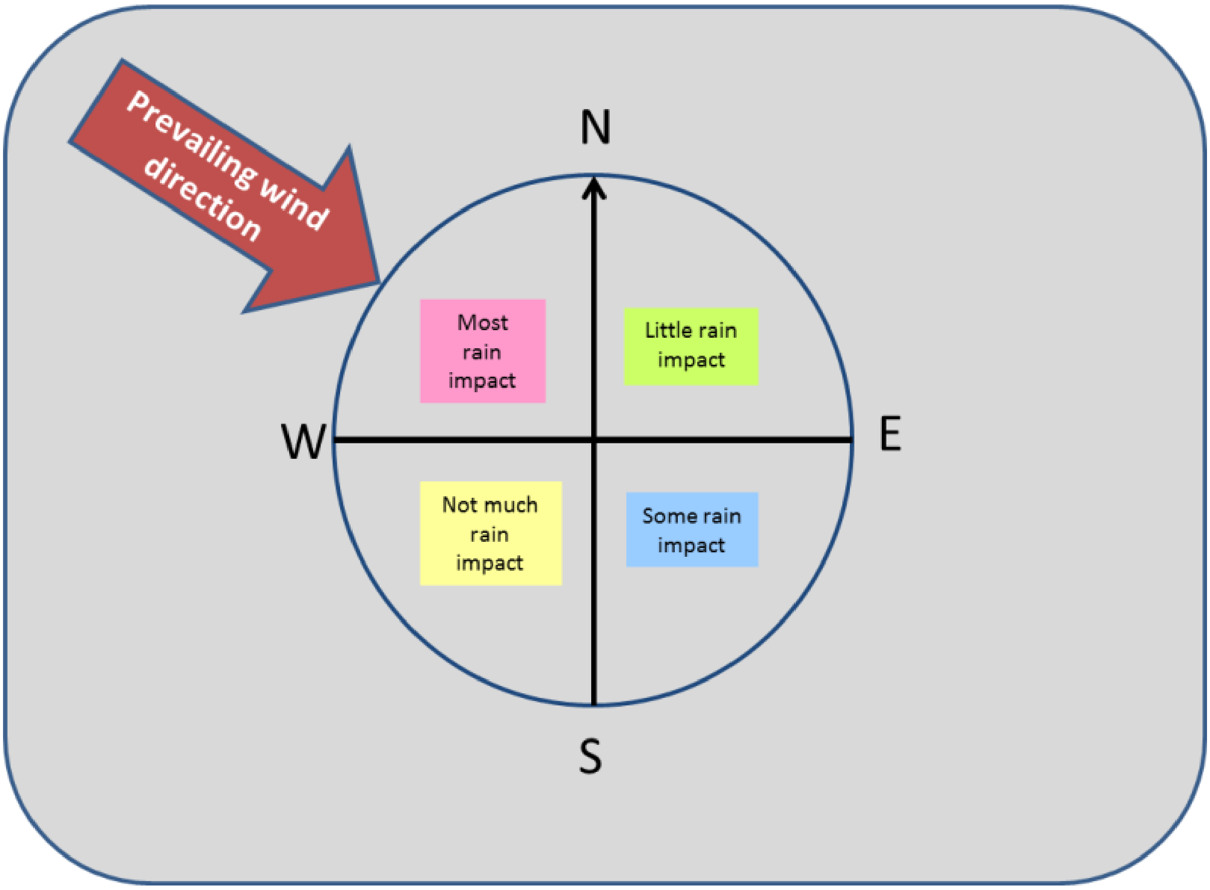

Figure 3 Prevailing wind direction

If the prevailing wind comes from the northwest, the parameters are selected as shown in Figure 3 and the symbology of the output raster of slope aspect is shown in Figure 4.

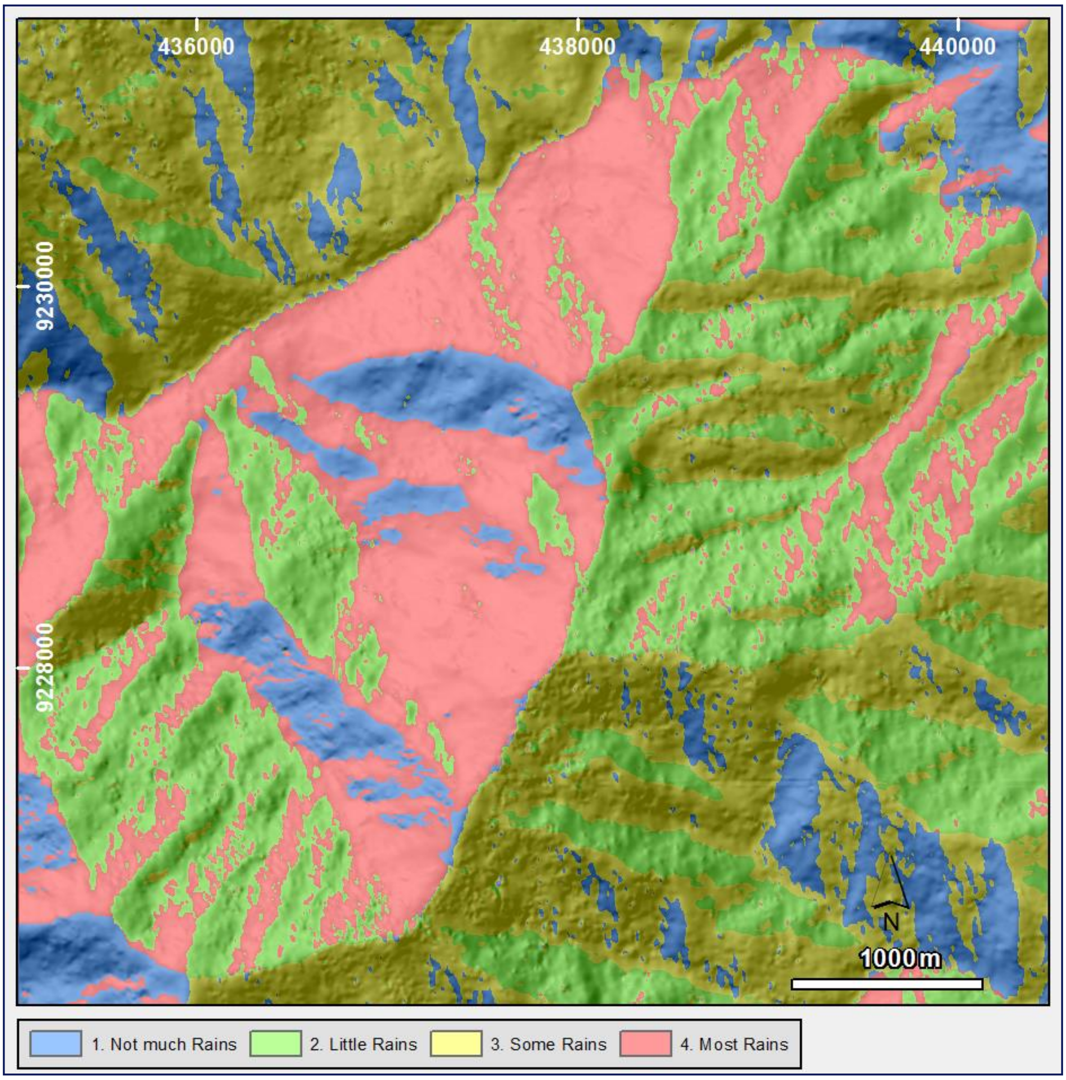

Figure 4 Slope aspect map (e.g. Gumots, PNG)

5.3 Landslides (L)

Thorough landslide analyses for hazard zoning requires extensive data gathering, laboratory testing of material and numerical analyses of potential failure surfaces (Kim and Kim, 1991). Landslide runoff distance estimations also require additional numerical modeling. However, this study only relates to regional analysis of landslides using GIS technology. Landslides in the project area were mapped and classified as a high geohazard zone. This hazard is not only confined to the landslide boundary but the zones bordering the landslide. Landslide can have DS runoff; can propagate US and can also propagate LAT. The bordering zones surrounding a landslide are known as buffer zones. Local experience of the landslide behavior is used in estimating the buffer zone widths and lengths. In areas known to have higher DS runoff, the length of the DS buffer zone can be relatively longer. The US and the LAT buffer zone widths are also estimated based on the local experience of the field exploration geologists in the region. For Gumots (PNG) area the buffer zones were classified according to the relative slope direction with respect to landslides as per Table 4 and Figure 5. Highest landslide hazard rating is assigned to the zone within 50 m DS or US and LAT within 10 m from the landslide boundary. The least landslide hazard is assigned to the zones outside 200 m DS, 100 m US and 50 m outside the landslide lateral boundary (Figures 5 and 6).

Table 4 Geohazard rating based on proximity to identified landslides

Geohazard Rating	Proximity to Landslide
0	Site is >200 m DS, >100 m away from US and >50 m LAT away from landslide.
3	Site is <200 m DS, <100 m US and <50 m LAT away from landslide.
4	Site is <100 m DS, <50 m US and <25 m LAT away from landslide.
5	Site is <50 m DS, <10 m US and LAT away from landslide.

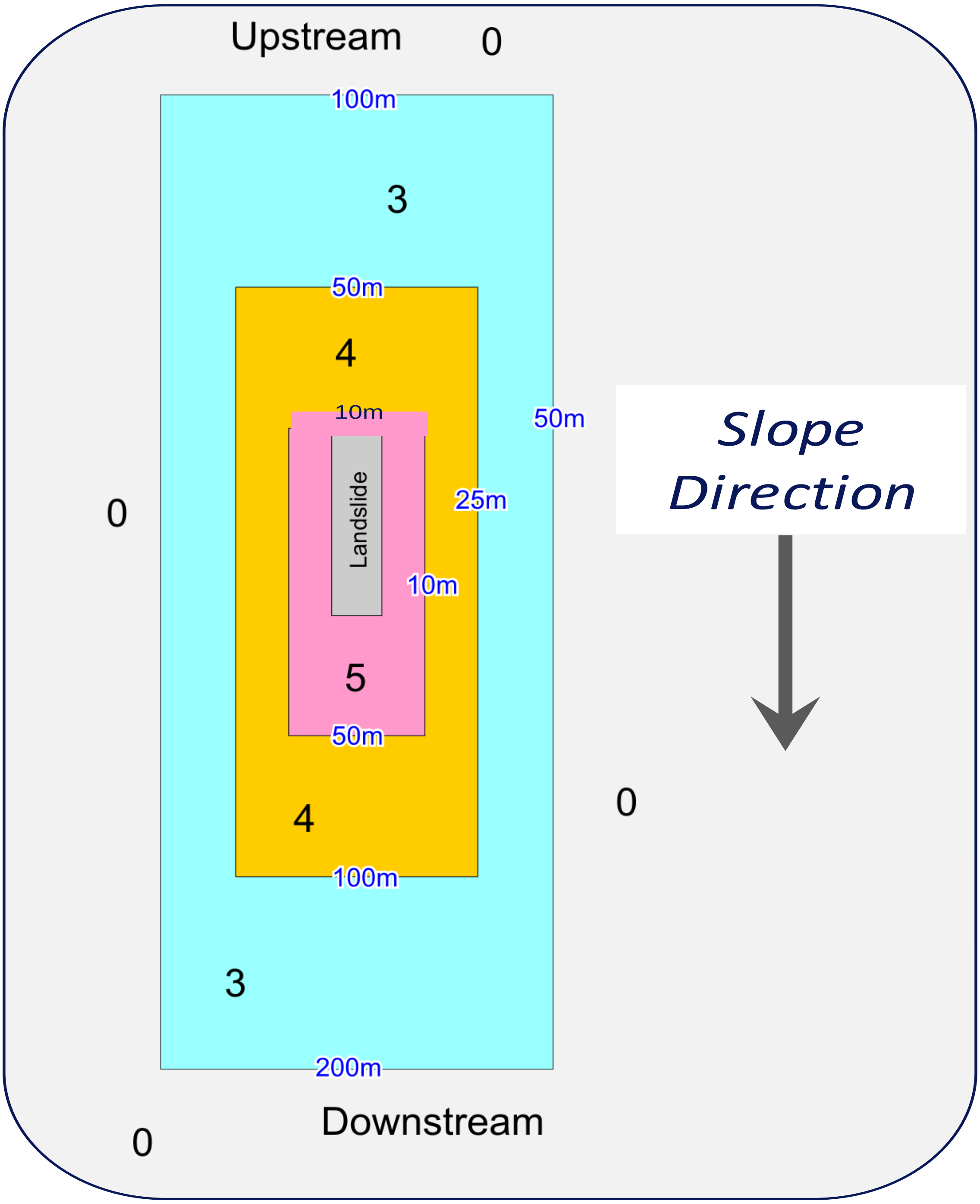

Figure 5 Landslide parameters

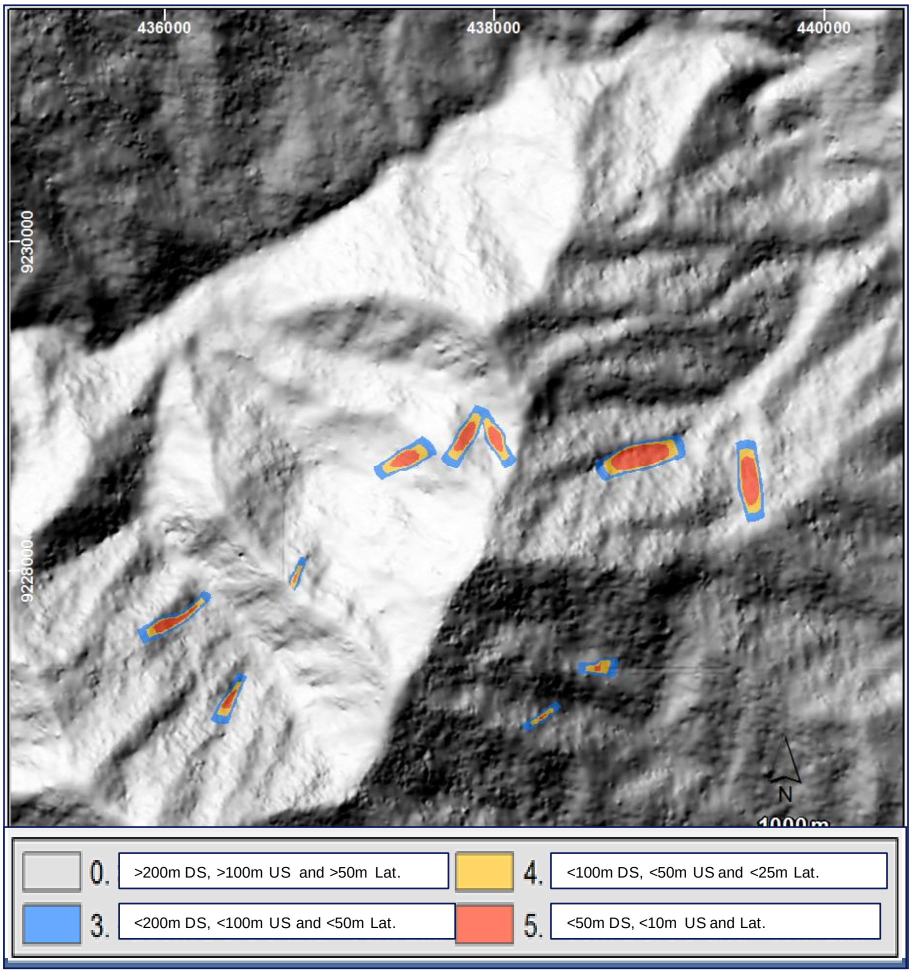

Figure 6 Landslide mapping and buffer zones (e.g. Gumots, PNG)

Proximity of the landslides to sites is very important for geohazard analysis. Therefore, landslide buffer classification was also given a number 1 ranking with a weighting of 3 in the raster compilation.

5.4 Ridge spur (R)

Field observations in the region revealed the ridge spurs in rugged terrains are geotechnically sound. Ridge spurs in the project area were digitised and assigned slope angle information on to the slopes within ridge spurs. Flat slopes on the ridge spur as per the classification in Table 5 have the lowest geohazard rating number 1 in the sequence (Table 5) with the lowest risk rating. Areas outside ridge spurs have been assigned a higher hazard rating of 5 (Figure 7). Ridge spur mapping information was also given a number 1 ranking and a weighting of 3 in the raster compilation.

Table 5 Geohazard rating based on proximity to ridge spur

Geohazard Rating	Slope Classification	Proximity to Ridge Spur
1	Flat slope (0–1°)	On ridge spur
2	Gentle slope (1–5°)	On ridge spur
3	Moderate slope (5–17°)	On ridge spur
4	Steep slope (17–35°)	On ridge spur
5	Side slopes	Outside ridge spur

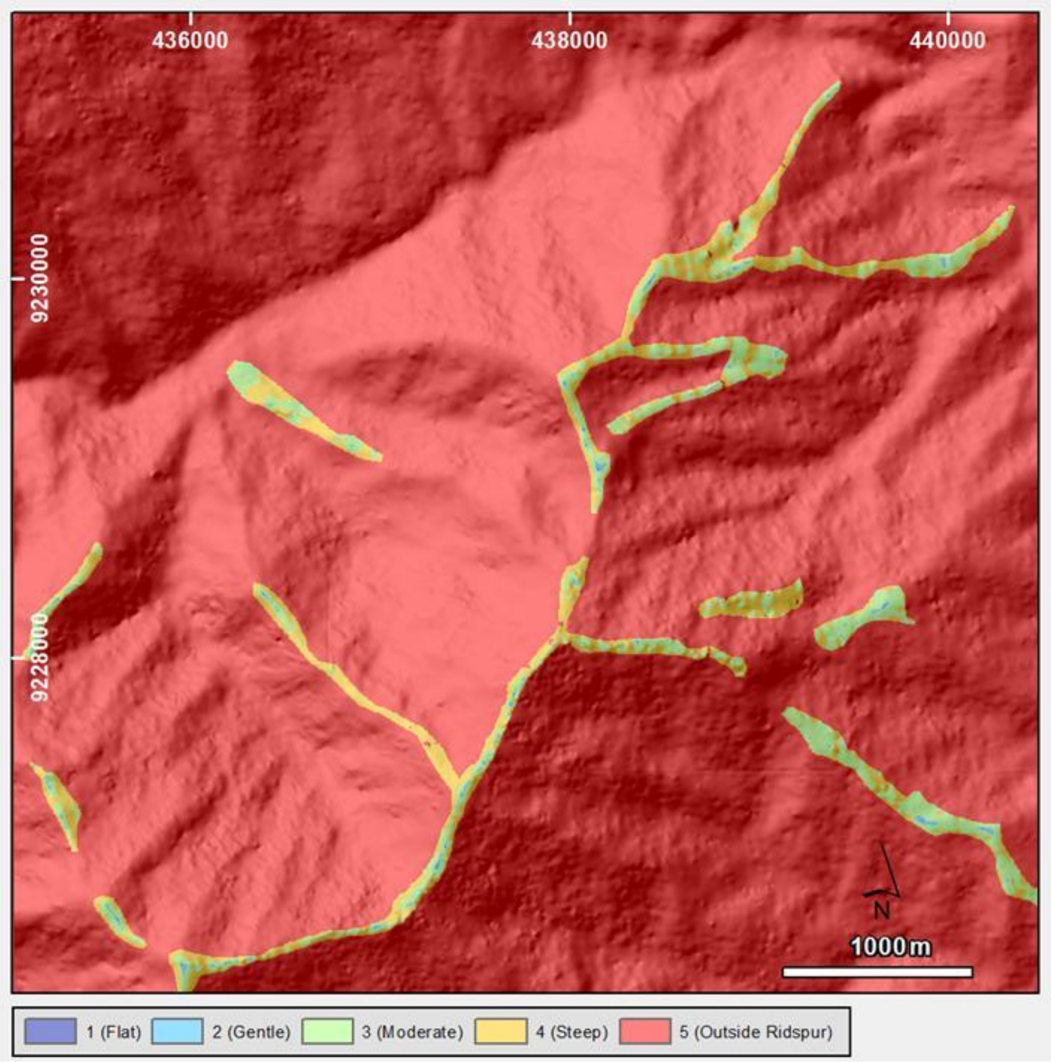

Figure 7 Ridge spur mapping and slope analysis in project area (e.g. Gumots, PNG)

5.5 Drainage (D)

The drainage system for each project area was mapped out in the early stages. Subsequently lateral River Buffer (RB) zones were assigned parallel to the existing drainage system (Figure 8). The stream buffer zones were classified as per the following classes with the lowest number in the sequence with lowest geohazard rating as shown in Table 6.

Table 6 Geohazard rating based on proximity to rivers

Geohazard Rating	Proximity to River
1	Outside 30 m RB
2	Inside 30 m RB outside 20 m RB
3	Inside 20 m RB outside 10 m RB
4	Inside 10 m RB/on the river

In estimating flash flooding potential at sites, proximity of them to river systems is given an important consideration. Therefore, RB zoning was given a number 2 ranking and a weighting of 2 in the raster compilation in this example.

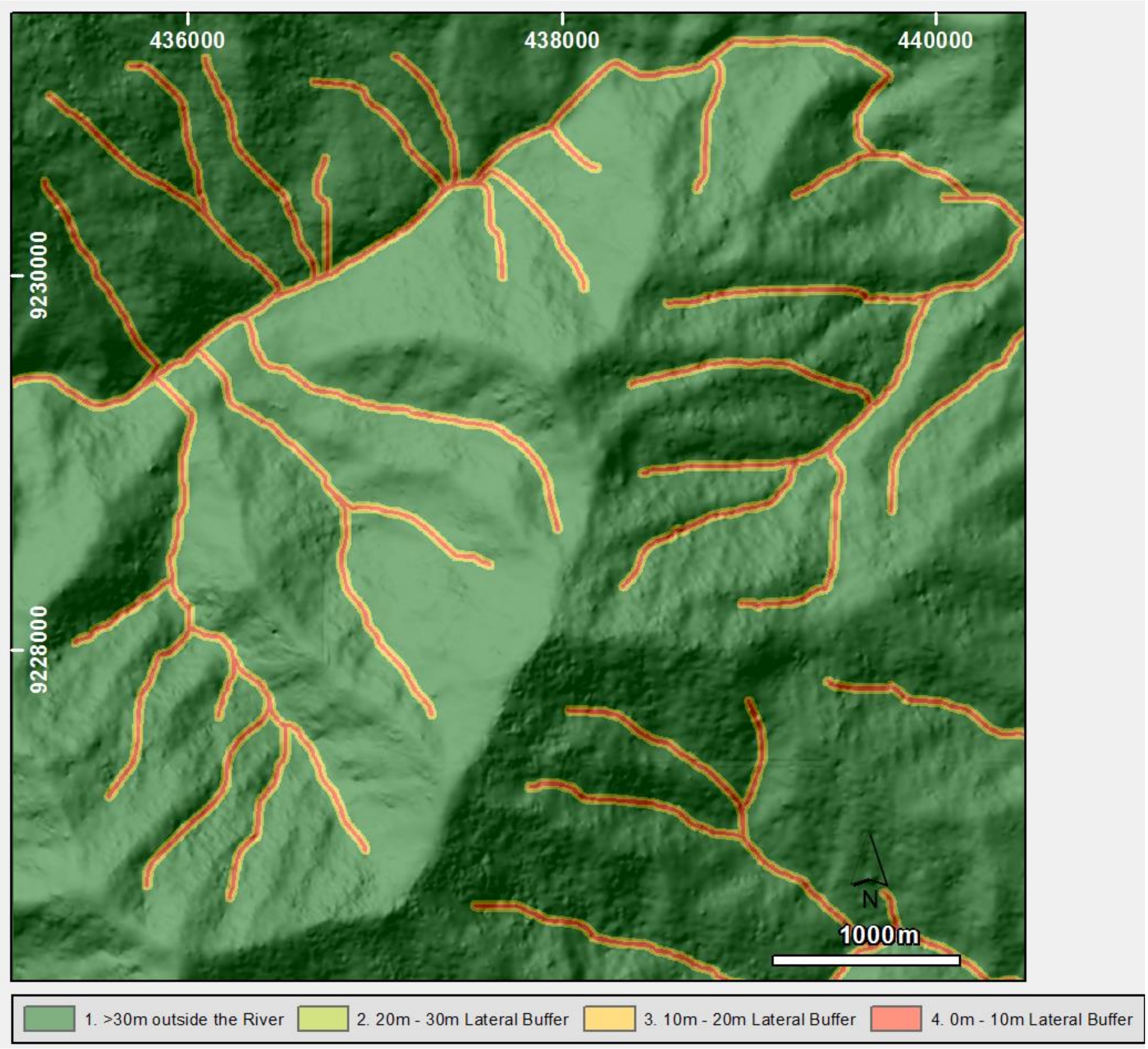

Figure 8 Drainage system analyses (e.g. Gumots, PNG)

5.6 Lithology/soils distribution (G)

For lithological distribution of the area detailed investigation of the engineering properties of the soils and rock types was not considered. Instead, the author utilised the public domain soils maps in determining the distribution of various soils types in the study regions. These can be supplemented by the regional geology or other available geology maps in the area. The field exploration geologist would verify this information based on their local experience. Equipped with this information the soils can be classified into broad soil groups based on gravel, sand rich soils, mixed soils with sand and clay or silty or loamy and clay rich soils (Table 7 and Figure 9). Lithology is given number 3 ranking with a weighting of 1 in the raster compilation.

Table 7 Lithology (soils) rating (e.g. Gumots, PNG)

Lithology (Soils) Rating	Soil Type
Good (1)	Granular soils: gravelly and sandy soils.
Moderate (2)	Mixed soils: mixture of sand, clay and loamy soils.
Weak (3)	Clayey fine grained soils: clay, silt and loam rich soils.

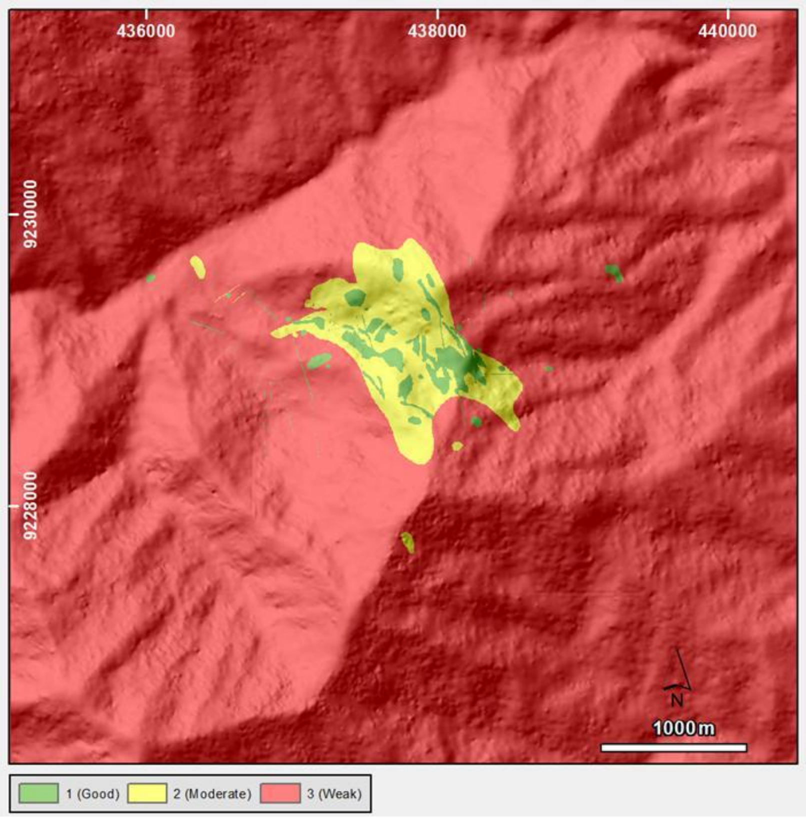

Figure 9 Lithology (soils) classifications (e.g. Gumots, PNG)

5.7 Raster compilation – project GHMT

Once the categories indicating S, A, D, R, L and G, are classified as per subsections above, they are ranked and weighted. Weighting system on categories used in construction of a spatial analysis map can vary depending on the project location. The risk levels of the project area landslides and flash flooding can have a significant influence on the weighting of the categories. Categories can be added and weighted depending on the information availability and the perceived influence of each category on the project risk level.

The classified data are then converted to raster format for spatial analysis as shown on Table 8. The raster format is then reclassified into a format suitable for raster compilation. The raster compilation is carried out as per the relationship below:

$$\text{Raster compilation} = 3S + A + 2D + 3R + 3L + G \quad (1)$$

Where:

S = slope angle (1 = flat, 2 = gentle, 3 = moderate, 4 = steep, 5 = very steep).

A = slope aspect (1 = not much rain influence, 2 = little rain influence, 3 = some rain influence, 4 = most rain influence).

D = drainage (RB, 1 = >30 m, 2 = 20–30 m, 3 = 10–20 m, 4 = 0–10 m).

R = ridge spur (1 = flat, 2 = gentle, 3 = moderate, 4 = steep, 5 = outside ridge spur).

L = landslides (1 = 100–200 m US, 2 = 50–100 m US, 3 = 100–200 m DS, 4 = 50–100 m DS, 5 = <50 m DS).

G = lithology (1 = good, 2 = moderate, 3 = weak).

With the raster compilation the hazard ratings is populated over the project area assigning high, moderate and low hazard rating to each pixel, resulting in a project GHMT.

Table 8 Classification and weighting matrix

Theme	Tools 1	Buffer Width / Explanation	Classification	Rank	Weighting	Tools 2
Slope Angle	**ArcGIS** \spatial analyst tools.tbx\surface\slope		Flat (0-1°) = **1** Gentle (1-5°) = **2** Moderate (5-17°) = **3** Steep (17-35°) = **4** Very Steep (>35°) = **5**	**1**	**3**	
Slope Aspect	\spatial analyst tools.tbx\surface\Aspect	Prevailing Winds (PW) vs. Slope Aspect PW generally bring rain; therefore, slope aspect facing PW increase the likelihood of Landslides	SE Quadrant:Not much Rains = **1** NE Quadrant: Little Rain = **2** SW Quadrant:Some Rains = **3** NW Quadrant:Most Rains = **4**	**3**	**1**	
Drainage	\analysis tools.tbx\proximity\multiple ring buffer	Lateral Buffer: 10m, 20m, 30m	>30m outside River = **1** 20-30m Lateral Buffer = **2** 10-20m Lateral Buffer = **3** 0-10m Lateral Buffer = **4**	**2**	**2**	**ArcGIS**
Ridgespur	Digitised		<u>**On the Ridge Spur**</u> Flat = 1 Gentle = 2 Moderate = 3 Steep = 4 Outside Ridge-spur = 5	**1**	**3**	\spatial analyst tools.tbx\reclass\reclassify & \spatial analyst tools.tbx\map algebra\raster calculator
LandSlide	\analysis tools.tbx\proximity\multiple ring buffer	DS/US 50m, 100m, 200m DS buffer can be >200m on very steep slopes (>35°) Lat 10m,25m,50m	DS (Downstream) US (Upstream) Lat (Lateral) >200m DS, >100m US and >50m Lat. = **0** 100-200m DS, 50-100 US and 25-50m Lat. = **3** 50-100m DS, <50m US and <25m Lat. = **4** <50m DS and <10m Lat. = **5**	**1**	**3**	
Lithology	Digitised	Classification is based on the perception of the site geologists on engineering properties of the rocks and the respective weathered products. Good Lithology = 1 Moderate Lithology = 2 Weak Lithology = 3	**Good** (gravel or sand rich soils) = **1** **Moderate** (mixture of sand, silt and loamy soils) = **2** **Weak** (silt, clay or loam rich soils) **= 3**	**3**	**1**	

The process flowchart of construction of GHMT is presented in Figure 10. The flowchart explains the process starting with the topography of the study area and the ArcGIS steps followed in construction of GHMT. The resulting GHMT for project area is presented in Figure 11. The GHMT is a simple colour coded map to indicate the hazard levels of the project area which can be used by the exploration geologist to locate the exploration infrastructure at relatively safe sites.

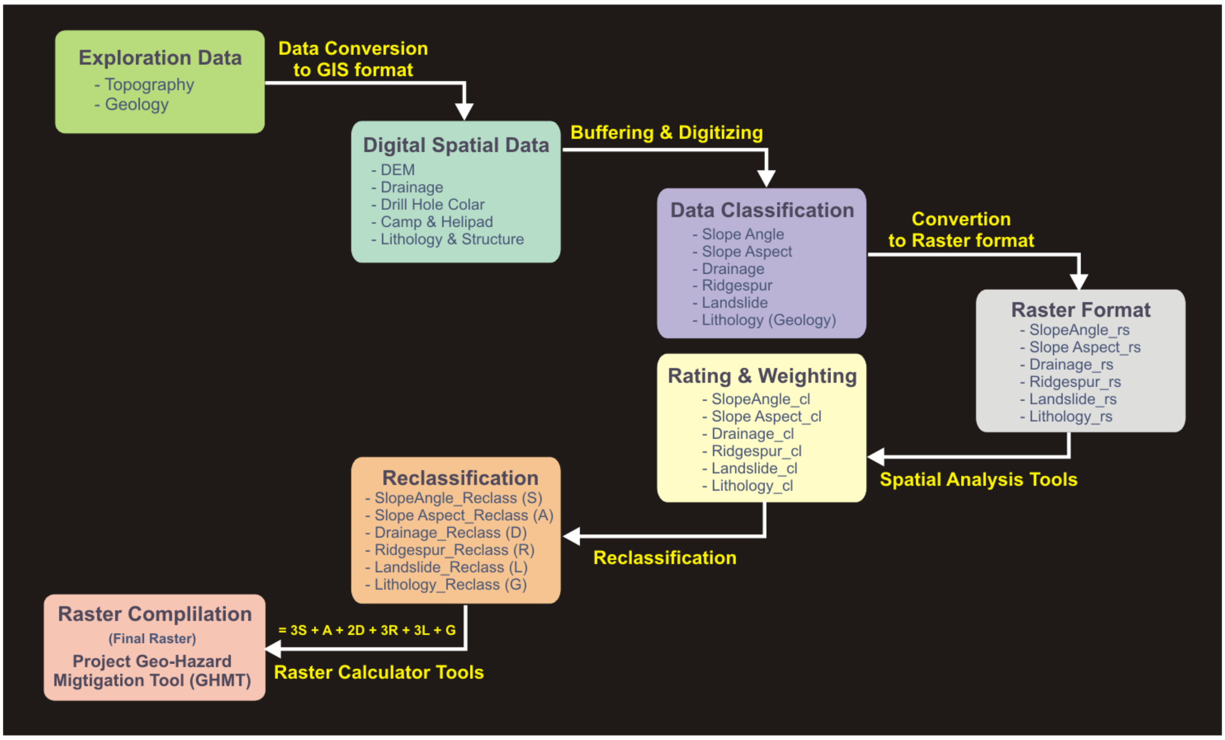

Figure 10 Process flow chart of construction of GHMT

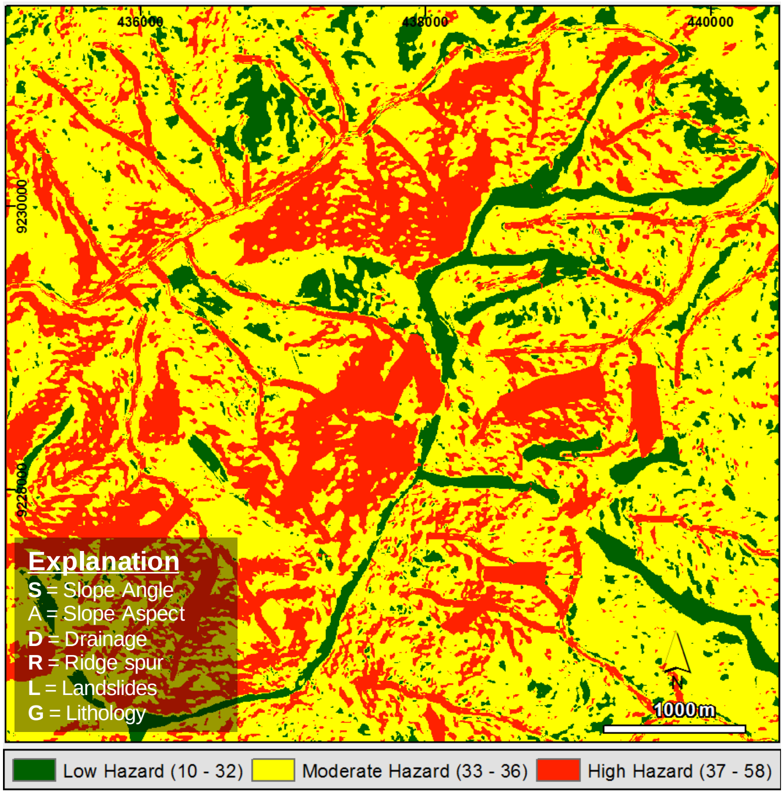

Figure 11 Raster compilation to form project GHMT

The project GHMT is prepared by the senior geotechnical engineer on request by the Geologist in Charge (GIC) of an exploration project. The GHMT is then used by GIC to locate the exploration sites in areas with low geohazard profiles.

6 Conclusions

This paper is based on the work the author carried out in Newmont exploration sites in PNG, Solomon Islands and in Indonesia.

The paper explains the process that was adopted in formulating a GHMT and the process employed to enhance the geohazard awareness of the field staff and methods used to improve the earthworks practices at exploration sites.

Incidents related to poor earthworks practices at exploration sites were significantly reduced after adopting good hillside construction practices.

The delivery of Geohazard awareness training to all field exploration personnel have enhanced their knowledge on geohazards in their work environment and empowered them to carry out initial geotechnical site inspections.

Establishment of geotechnical standards on earthworks practices helped Newmont to standardise the work methods at the exploration sites.

The GHMT is a geohazard rated map of the project area prepared with high definition remote sensing images, GIS and geotechnical assessment to provide guidance to the site exploration geologists to locate drill pads, helipads and camps sites in suitable locations with lowest geohazard risk profile.

In rugged terrain, with thick vegetation cover, prone to landslides and flash flooding, it is generally very difficult to ascertain the ground conditions without spending a great deal of time, labour and effort in selecting relatively safe sites for exploration infrastructure. Positive feedback received from exploration field geologists has shown that these limitations can be overcome with the use of the GHMT in locating exploration sites efficiently.

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