iCASP

Integrated Catchment Solutions Programme

# An assessment of the potential of Natural Flood Management Schemes to generate slope instability.

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# Contents



# EXECUTIVE SUMMARY


The desire to store water in natural flood management schemes in upland areas is a logical and environmentally sensitive measure to mitigate downstream flooding in urban environments. However, retaining water in slopes has the potential to generate landslides on natural slopes. Three broad forms of instability were considered. The first was the potential for leaky barriers and attenuator dams to fail. The second was that water stored in valley bottoms via attenuator dams/leaky barriers may create instability on adjacent slopes. The final investigation was to look at seepage of stored water through peat and then into the subsequent rock mass to generate instability on the slopes below. For scenario 1, analysis indicated that the overturning moments created by heads of water stored behind leaky barriers or attenuator dams was too low to create sufficient shear forces, or overturning moments to result in failure. Potential for failure could arise through seepage and erosion at the bases or adjacent slopes resulting in a loss of support. For Scenarios 2 and 3 the outcomes of these analyses indicated that too little water was stored for long enough to generate instability on slopes that did not already show very marginal stability conditions. Such slopes are normally characterised by geomorphological evidence of instability (scars, tension cracks etc) and as such these morphological characteristics can be used as indicators of where further analysis is needed. Three conceptual hazard models highlighting key features to be considered around natural flood management schemes have been constructed. These models show models that can be applied to dams & barriers, upland NFM and valley NFM. A workflow is outlined to aid both practitioners and volunteers highlight potential signs of slope instability to allow further work to be undertaken.

# GLOSSARY OF TERMS

| Term | Description |
|---|---|
| Active landslide | A landslide which is currently moving. |
| Angle of shearing resistance | One of the two components of the strength referred to in the Mohr-Coulomb shear strength criterion. More commonly referred to as friction angle. |
| Body (of landslide) | The section of a landslide between the head of the landslide and the toe of the landslide. This is normally material displaced from the head of the slide. |
| Cautious estimate | An estimate of strength based on the assumption that 90% of the actual strength data will be higher than the parameters used. |
| Cohesion | One of the two components of the strength referred to in the Mohr-Coulomb shear strength criterion. An apparent cohesion in un-bonded geological materials normally stems from partially saturated conditions. |
| Conceptual Ground Model | Conceptualisation of the ground conditions on site normally based on desk study or a priori information. Additional site specific information results in an explicit model, and additional design data creates an analytical model (See Parry et al 2014) |
| Conceptual Hazard Model | A conceptual model of the ground which identifies geotechnical hazards for the purpose of later analysis. |
| Creep | A form of mass movement where displacement is accommodated via a series of grain to grain level movements. The physical expression of creep is the formation of terracettes. |
| Crown | The top of the head of a landslide. |
| Effective (normal) Stress | The stress acting in a slope modified by the effects of pore water pressure. This is considered to be acting perpendicular to a potential slide plane so that a reduction in the effective stress results in a decrease in stability. |
| Factor of Safety | The ratio of strength to stress in a slope based on soil properties and water pressures. A stable slope normally has Factors of Safety in excess of 1.25 and a marginally stable slope will show Factors of Safety between 1.0 and 1.25. |
| Foot | The lower part of a landslide which is predominantly a depositional zone. |
| Head (of landslide) | The upper part of the landslide. This area is normally the source of soil and rock material which makes up the slide mass. |
| Impenetrable | A material which cannot have a slip surface cutting through it for the purposes of slope stability analysis. |
| Inactive landslide | A landslide which is not currently moving. This can be subdivided into:<br>• Inactive (Suspended): a landslide which is not currently moving but has moved within the last 12 months.<br>• Inactive (stabilised): a landslide which has had active stabilisation measures deployed.<br>• Inactive (abandoned): a landslide which no longer subject to the driving mechanism (e.g. a landslide caused by river erosion, where the river has meandered away from the slope). |
| Landslide | A downward and outward movement of soil, rock or some combination of the two which has clear boundaries at the top, bottom, sides and base. |
| Natural slope | A slope which has not been substantially modified in terms of size or shape by mankind |
| Relict landslide | A landslide which has formed in prior a climatic period. Such landslides can be re-activated. |
| Shear Surface | The boundary between the sliding mass and the stable ground below. Often also referred to as slip surface or rupture surface. |
| Tension crack | A crack in the ground forming due to slope movement. These normally form between areas of moving ground and stable ground, but may also form where moving ground is moving at different rates or different directions. |

| | |
|---|---|
| Till | An engineering soil deposited by direct contact with ice. Often incorrectly termed “Boulder Clay”. |
| Toe | The end of the foot of a landslide at the furthest extent of the crown. |

**Abbreviations**

| | |
|---|---|
| CGM | Conceptual Ground Model |
| CHM | Conceptual Hazard Model |
| F | Factor of Safety |
| $kN/m^3$ | Kilo Newtons per meter cubed. |
| kPa | Kilo Pascals |
| Ma | Millions of years ago |
| NFM | Natural Flood Management Scheme. |

# 1. Flooding and Landslides

1.1 The Calder Catchment is characteristic of conditions found in many upland areas with broad ground conditions than can be described as peat overlying a more competent substrate. That substrate is often characterised as sections of interbedded sandstones and mudstones of lower Carboniferous (314-360 million yeas) age. In some parts of the Calder Catchment, tills can be found that provide a mineral layer between the bedrock and organic soils, and in other areas a layer of high plasticity mineral matter can provide a sliding surface.

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1.3 The conditions seen in the Upper Calder catchment can be represented in three conceptual hazard models. These are: CHM1 Moorland Model; CHM2 Valley Slope Model and CH3 Leaky Barrier Model. Conceptual Hazard Models are shown in Appendix A and seek to describe the majority of conditions that may be encountered.

1.4 Landslide activity seen in the Upper Calder catchment broadly fall into four categories of slope failure as described by Hungr et al (2014)1. These are rock falls (single and multiple block); rock slides (single and multiple blocks); debris avalanches (see figure 1 for example) and debris slides. In areas where tills are thicker, debris and silt slumps may occur.

1.5 Large sections of the Pennines contain relict landslides identified by the British Geological Survey during the production of geological maps. Many of these are rock falls which may continue to enlarge or deep seated rock slides. The potential to reactivate old relict landslides (those formed under a different geomorphological/ climatic regime than observed today) is likely to be low but has not been investigated as part of this work.

1.6 Flooding has the potential to cause landslides through a number of mechanisms. These include seepage and particle movement (loss of material strength); erosion at the foot of slopes (changing confining stress) and increase in water levels within slopes (changes in effective stress). In this work the changing effective stress state has been the main consideration in CHM1 and CHM2 with erosional processes being the main consideration of CHM3.

1.7 In CHM1 the main hazard considered is water seepage through peat from a NFM scheme deployed at the top of the slope. Analysis is intended to identify whether sufficient change in the effective normal stress occurs to create instability.

1.8 In CHM2 a scenario is described where the retention of flood waters at the foot of a slope produces a sufficient reduction in effective normal stress at the toe of the slope leading to instability OR whether active erosion could contribute to instability.

1.9 A CHM3 the performance of leaky barriers was considered. The following concepts where explored:

- A 1 m high barrier which becomes full during intense rainfall
- A 1 m high barrier which becomes infilled with sediment by floodwater
- A 1 m high barrier where water flows beneath the barrier by seepage creating localised over-steepening due to erosion.

1.10 Key assumptions used in these analyses was (1) materials properties were static; (2) there was a 2% decrease in depth to water table due to seepage from retained flood water. Material parameters were derived as a cautious estimate based on prior experience of similar geological materials.

1.11 The outputs of the analyses presented has to be seen against a review of the scientific literature. Where NFM schemes are seen as an approach to mitigating flood hazard, generally the control of landslide activity due to river erosion is seen as beneficial. There is limited evidence in the technical literature of NFM schemes triggering slope instability.

# 2. Models used and input parameters

2.1 Stability analysis was carried out using Bishop's Method (see Bishop, 1955). This was used as the underpinning analysis as it was assumed that small failures in the soil would occur as circular or semi-circular slips. This approach is conservative, and since the aim of the project was to investigate whether landslides could occur due to NFM methods, that conservatism was considered valid.

2.2 Bishop's method will not adequately model landslides that occur at the soil-rock interface. How strength is mobilised on such landslides is difficult to characterise without site-specific data collections, so such landslides are not included in the analysis.

2.3 Given that the current investigation focuses on whether a landslide could be triggered, and there was no question about size or runout, Bishop's Method can provide a first look form of assessment, although it should not be considered to be a precise answer but a conservative one.

| **Material** | **Cohesion (kPa)** | **Angle of shearing resistance (°)** | **Unit weight kN/m³. (saturated)** | **Comments** |
|---|---|---|---|---|
| Coarse soil | 0 | 33 | 22 | Normally fluvial soils found in and around streams of 1-2 m in depth. |
| Fine grained soils | 20 | 25 | 18 | Generally tills which may be weathered in their own right. |
| Clay | 20 | 12 | 18 | A mottled, blue-grey soft clay which is commonly found throughout the Calderdale area. |
| bedrock | 4000 | 35 | 26 | Considered to be impenetrable for this analysis. |

Table 1. Input parameters used for the calculation of slope stability for each conceptual hazard model.

2.4 It is worth noting here that the very conditions that would bring Natural Flood Management schemes into action, namely periods of intense rainfall, are the very conditions that would trigger landslides independently of any NFM scheme. Therefore, any validation using case examples of landslides in the vicinity of any NFM scheme will be difficult in the absence of site specific monitoring data.

2.5 On slopes greater than c. 40o, the main mode of land sliding would be rock fall (rock falls can occur on lower angle slopes where there is localised steep rocky sections). There is abundant evidence of rock fall on steeper slopes in the Pennines. Rock falls are generally triggered by freeze-thaw or occasionally thermal loading (see Colins and Stock, 2016) and so have not been included in this investigation.

2.6 Based on existing geological and geotechnical data held in the School of Earth and Environment, ground conditions in conceptual hazard models were described as shown in Table 1.

## 3. Results for Conceptual Hazard Model 1 – Moorland Model

3.1 Analysis of CHM1 was based on similar assumptions and methods outlined in section 2.2 The evidence of marginal stability will be highlighted on CHM1 in Appendix A.

3.2 Analysis was based on the assumption that infiltration would be increased by 2% due to water retention through NFM and that this would translate directly to an increase in water table depth by 2%. The resultant increase in pore water pressures was insufficient to create instability on the models used. Even treating this increase as a steady state change, which is highly conservative, instability is only likely with F<1.05.

3.3 What is more difficult to consider is the combination of water storage and increased rainfall directly onto the slope. The effective rainfall contribution to slope instability combined with the effects of NFM scheme is difficult to assess given the current level of investigation given that such effects are likely to be highly site specific.

3.4 It is also difficult to assess the role of uplift pressures acting at the soil-rock interface. Figure 1 was considered to be the result of water flow at this kind of permeability boundary, and there was good (evidence of landslide head, body and toe) geomorphological evidence for 8 similar landslides within 1 km of this particular site, with a further 7 likely landslides (evidence of body and head but no toe evident) landslides. This type of landslide is likely to be controlled by site specific characteristics that will govern effective rainfall.

## 4. Results for Conceptual Hazard Model 2 – Valley Slope Model

4.1 Analysis indicated that the use of leaky barriers (purpose of water retention) in streams or the near the bottom of slopes does not significantly increase pore water pressure in the slope which would lead to landslide development.

4.2 The transient nature of retention ponds at the foot of slopes is also unlikely to induce the development of slope instability through changes in pore water pressure.

4.3 An additional potential cause of instability would be the erosion of the lower parts of slopes by retained flood water. A review of the technical literature shows no case examples where landsliding has developed due to the implementation of attenuator or retention pond in this geomorphological setting.

4.4 Given the calculated Factors of Safety for the conceptual hazard models it is likely that toe erosion would need to create a significant reduction in confining pressure and may need erosion around valley bottoms in excess of 1 m or so.

4.5 In the event that water storage from a NFM could be anticipated to abut against the foot of a slope, then the use of woody vegetation (Ollauri & Mickovski, 2017) could be used as mitigation by reducing pore pressures and providing erosion protection.

## 5. Results for Conceptual Hazard Model 3 – Leaky Barrier Model

5.1 Analysis using limit state models for water-full or sediment-full barriers does not indicate failure of the barrier either at the barrier-ground interface through shear or via overturning. The biggest potential for failure is through basal erosion of the channel in front of any leaky barrier resulting in localised over-steepening leading to movement of the channel banks. Available data suggests this is unlikely, but traditional limit state calculations were not designed for such conditions (very steep angles, but low height slopes) and must be viewed with caution.

5.2 Analysis of erosion downstream from a leaky barrier was considered. The situation modelled was potential over-steepening of the slopes on which the edges of the leaky barrier sits. This indicated that this could result in localised scour.

5.3 A discussion with colleagues at BGC Engineering in Vancouver, indicated that the biggest potential for failure was deterioration of the material forming the leaky barrier.

5.4 Although the use of limit state models has allowed a consideration of the localised stability issues surrounding leaky barriers, these models were not designed for this particular failure mode.

5.5 On the basis of the available data and analysis the most effective management of the potential for failure of a leaky dam is through monitoring on an annual basis.

## 6. Workflows

6.1 The implementation of NFM schemes often involves a mix of professional scientists / engineers and volunteer workers seeking to play their part in the protection of communities. Given this variation in skillsets it is useful to set out a set of baseline observations to be undertaken prior to implementation of any NFM scheme.

6.2 Appendix A shows flow diagrams which outline observations to be made when considering whether to deploy NFM schemes for each conceptual hazard model. These workflows can also be applied to assess existing NFM Schemes that are already in place.

6.3 In the event of a potential stability problem being identified a more detailed assessment should be carried out by a Suitably Qualified Person. Examples of suitably qualified persons can be found in CIRIA 1096 - Natural slopes – condition, appraisal and remedial treatment.

## 7. Summary and recommendations

7.1 Available information indicates that there is no significant slope stability concerns created by natural flood management schemes.

7.2 The evidentiary challenge however, is that the extreme weather conditions which would normally see NFM schemes prove their worth would tend to trigger landslides regardless of any NFM schemes as was evident in the storms of winter 2015/16.

7.3 Analysis indicates that the implementation of NFM in proximity to existing landslides may result in reactivation of the slope movement.

7.4 Analysis of leaky barriers which either retain a full water load or a full sediment load does not indicate sufficient overturning moment to induce failure. However, over-steepening due to erosion downstream of the barrier may result in localised movement on the barrier. The risk of cascading failure can be mitigated through distributing leaky barriers in tributary streams as outlined in Hankin et al (2020).

7.5 Parameters used in the analysis are fundamentally conservative in their selection. This means that results here represent a scenario close to worst case. However, the variation in materials, material properties and localised groundwater conditions may still combine to create slope instability. The absence of detailed, site specific data means that this cannot be completely excluded but, it the evidence suggests that it is unlikely.

7.6 It is recommended that the installation of NFM schemes in the vicinity of existing landslides is avoided in order to minimise risk of re-activation.

7.7 If implementation of a NFM scheme is mandated by the requirements to manage water flow near an existing unstable slope, then expert guidance should be sought from a suitably qualified person.

7.8 It is recommended that inspections of NFM schemes in upland areas should involve a check for slope instability. The installation of NFM schemes in the vicinity of slopes which then retain water to some extent, turns those slopes into geotechnical assets, which must be managed as such.

7.9 Workflows to be considered as part of the implementation of Natural Flood Management Schemes are outlined in Appendix B.

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# Appendix

## Appendix A: Conceptual models and indicators of instability

Figure A1. Evidence of slope instability on slopes below an implemented natural flood management scheme (Conceptual Hazard Model 1).

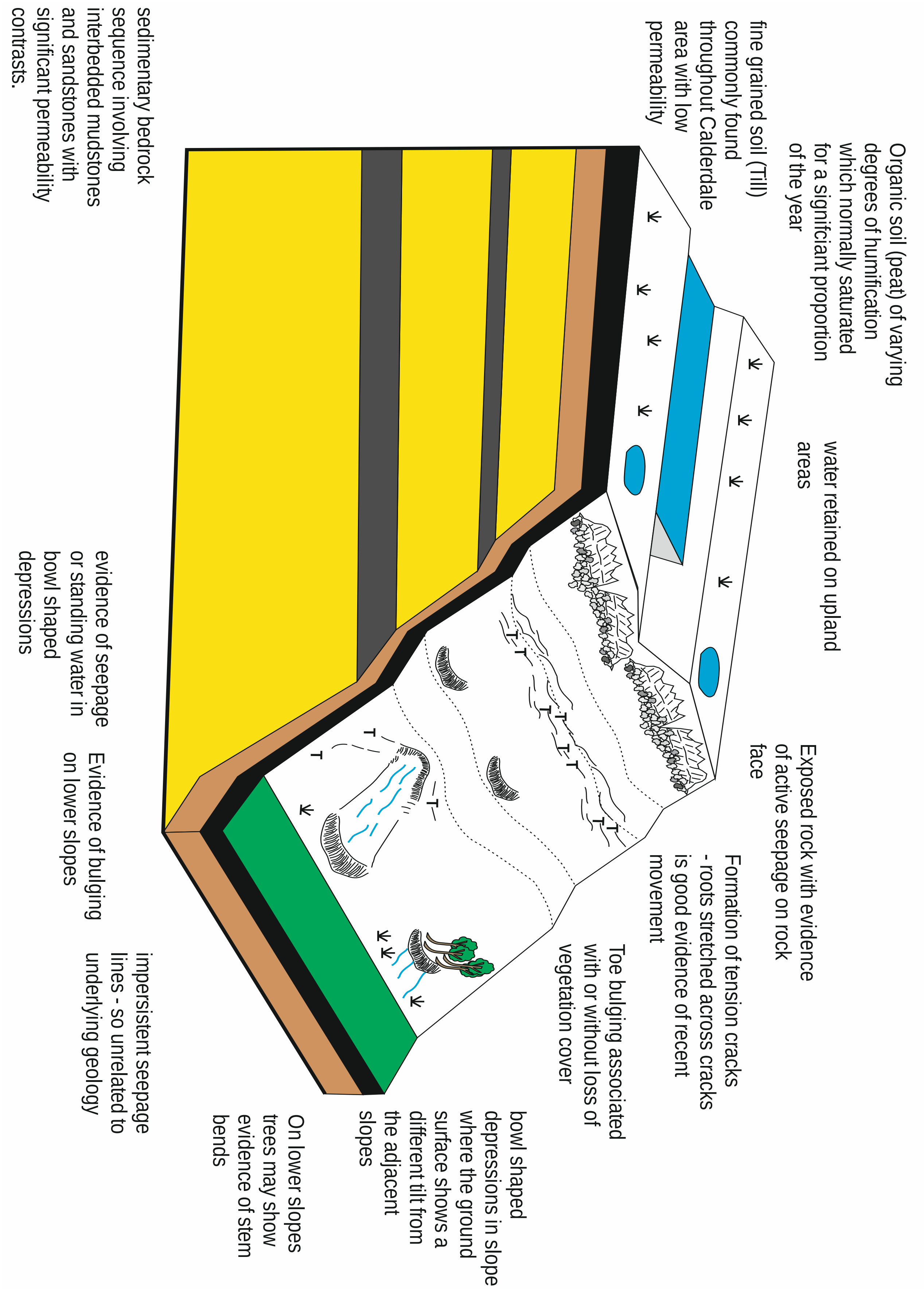
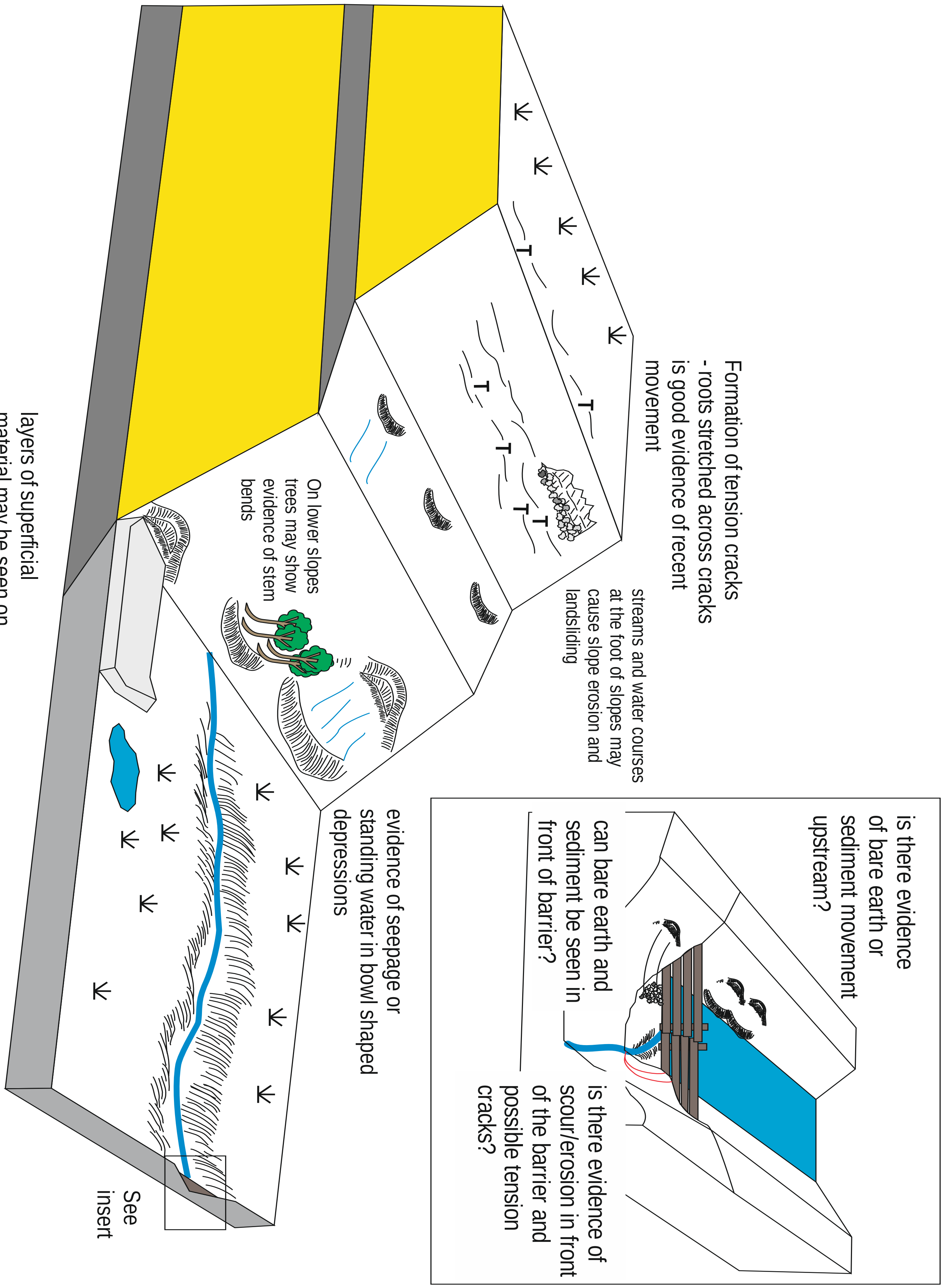
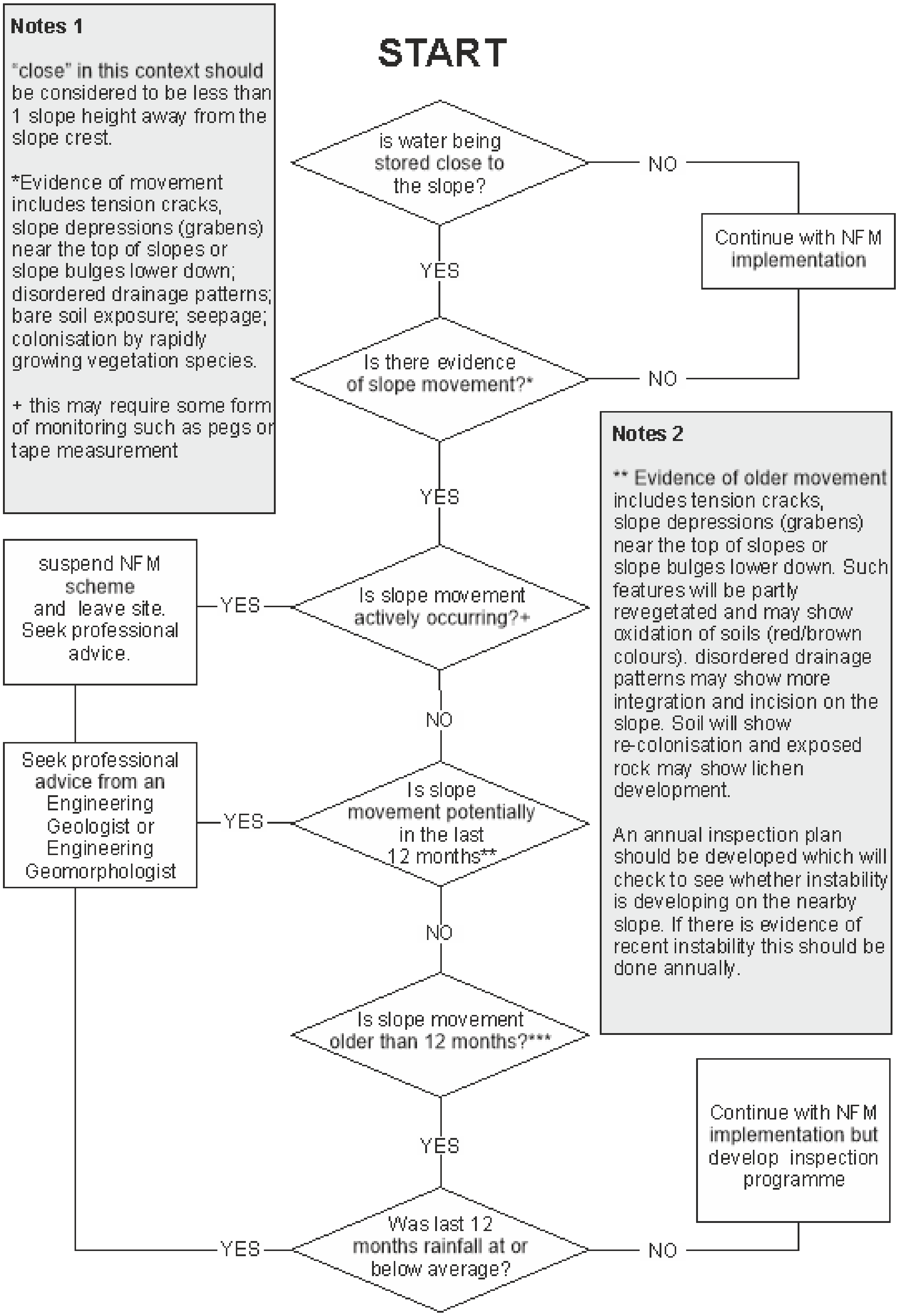


Figure A2. Evidence of slope instability on slopes above an implemented natural flood management scheme (Conceptual Hazard Model 2).



# Appendix B: Workflow to be followed where NFM scheme is above slope

Appendix B1. Workflow to be followed where NFM scheme is above a slope.



Appendix B2. Workflow to be followed where NFM scheme at the foot of a slope.