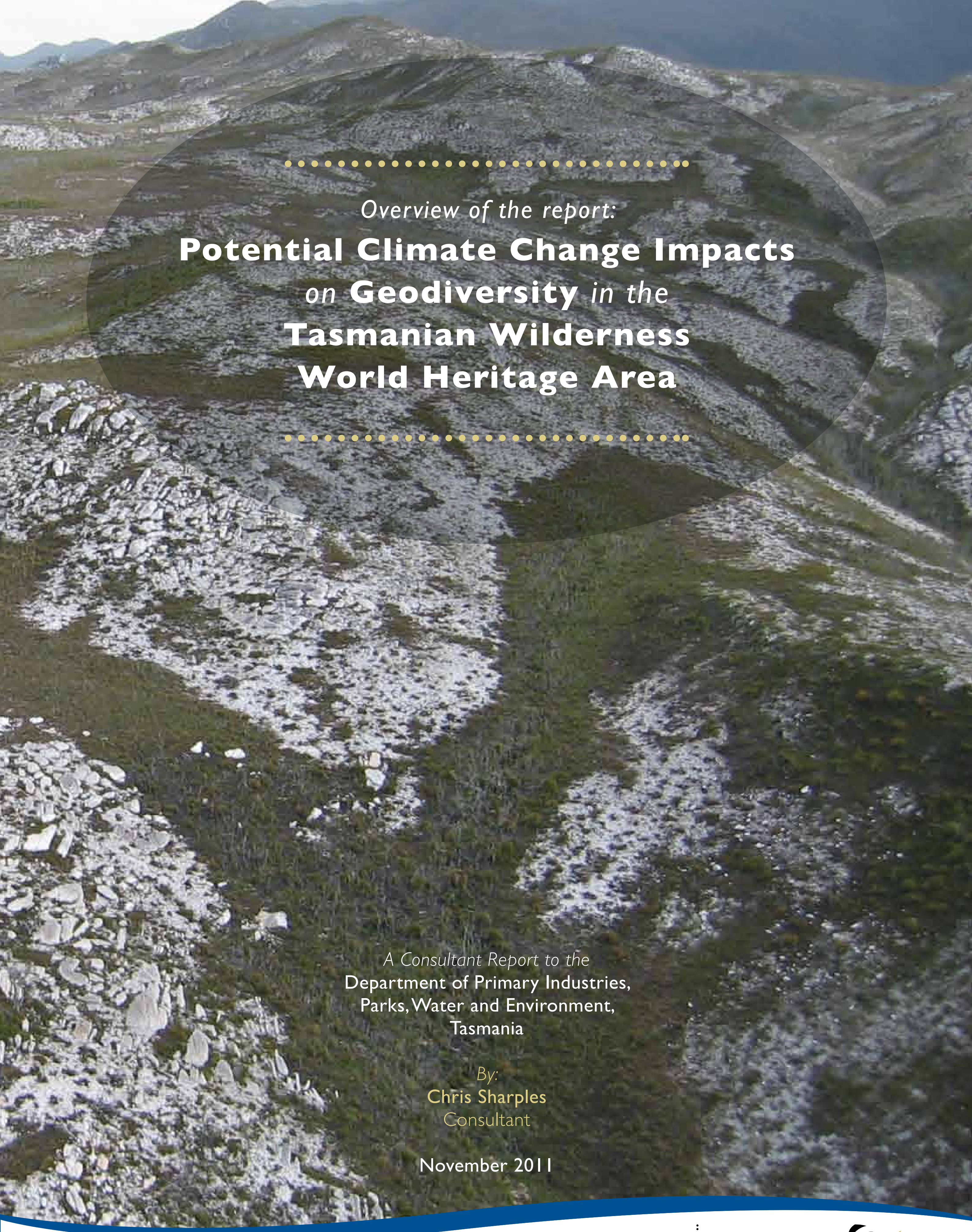

Overview of the report:

Potential Climate Change Impacts *on* Geodiversity *in the* Tasmanian Wilderness World Heritage Area

A Consultant Report to the
Department of Primary Industries, Parks, Water and Environment, Tasmania

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November 2011

Department of
Primary Industries, Parks, Water and Environment

United Nations Educational, Scientific and Cultural Organization
World Heritage

Tasmanian Government

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Cover Photo: Slopes to the west of Hardwood River in the Tasmanian Wilderness World Heritage Area (TWWHA) denuded of moorland organic soils following intense fires. One of the major issues identified by this study is the likelihood of increasingly widespread degradation of organic soils such as these due to increased fire risks combined with increased summer drying and desiccation - with potential impacts for aesthetics, fluvial processes, vegetation communities and habitats, and carbon sequestration. Although the degree of organic soil loss likely to occur depends on a range of poorly-understood processes and thresholds, in the worst case scenario climate change impacts on these soils would result in major changes to the character and natural processes of large portions of the TWWHA, and the release of large quantities of previously-sequestered carbon. *Photo by Michael Comfort.*

Overview of the report:
Potential Climate Change Impacts on Geodiversity in the Tasmanian Wilderness World Heritage Area

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Introduction

This short document is an overview of the report *Potential climate change impacts on geodiversity in the Tasmanian Wilderness Word Heritage Area: A management response position paper* and has been prepared in order to assist discussion and facilitate the dissemination of issues raised in the full report. The full report was written by Chris Sharples, a consultant with expertise in the fields of both geodiversity and climate change. The work was funded as part of the 2010-11 Tasmanian Wilderness World Heritage Area (TWWHA) programme and the Geodiversity Conservation and Management Section of the Department of Primary Industries Parks Water and Environment (DPIPWE) managed the project.

The full report:

Sharples, C. (2011). *Potential climate change impacts on geodiversity in the Tasmanian Wilderness Word Heritage Area: A management response position paper.* Resource Management and Conservation Division, Department of Primary Industries Parks Water and Environment, Hobart, Nature Conservation Report Series 11/04.

is available on the DPIPWE web site at:

http://www.dpiw.tas.gov.au/inter.nsf/WebPages/LJEM-6EM25L?open.

This overview is largely drawn from the executive and technical summaries of the full report. Given the complexities and uncertainties associated with many of the issues discussed, this overview, by its very nature has attempted to simplify and summarise information and it may be necessary to consult the full report to more fully understand the background (including information sources) behind some of the material and findings in this overview document.

Main findings from the report

- Climate change is likely to result in some degree of changes to geological, geomorphological and soil features and processes (geodiversity) in the TWWHA, albeit of widely varying magnitudes.

- It is in general unlikely to be beneficial (in terms of the TWWHA management objectives) to attempt to prevent or significantly mitigate those impacts because of the large (global) scale of the driving processes, the likely huge expense of the 'geo-engineering' that would be required, and in particular the probability that such interventions would compromise other natural TWWHA processes and values.

- The natural systems of the TWWHA will evolve in response to climate change, and since a significant degree of global climate change is now 'locked in' there seems little point or justification in attempting to prevent this.

- The goal of management in the TWWHA should therefore be to *manage the consequences of change* rather than to attempt to stop it happening.

- From this perspective, four fundamental management response options to potential impacts on TWWHA geodiversity have been identified, namely:
    1. *Do nothing*
    2. *Recording and sampling*
    3. *Monitoring and research*
    4. *Selective limited intervention*

- Identified potential impacts of climate change on geodiversity in the TWWHA have been prioritised according to their likelihood of occurrence and their consequences if they do occur using the Australia – New Zealand Risk Management Standard as a framework. The priorities identified by this process are not in the first instance priorities for *on-the-ground action*, but rather are priorities for *considering* whether any beneficial actions can be taken at all, and if so what. The full resulting prioritised list of potential climate change impacts on TWWHA geodiversity is provided in Table 1 of this overview. Selected higher priority potential impacts on TWWHA geodiversity identified by this process include (but are not limited to):

- Widespread degradation of moorland organic soils in the TWWHA is likely due to increased seasonal drying, warming and fire, especially on better-drained slopes. Flow-on consequences for other natural processes and values in the TWWHA are likely to be major because of the extensive distribution of the existing moorland soils.
- The greatest climatic changes for any TWWHA region by 2100 are projected to occur on the Central Plateau. Significantly increased warming and drying of the Plateau in all seasons will result in changed runoff and fluvial processes; vegetation stress and increasing fire risks leading to increased wind and water erosion; increased aeolian process activity including remobilisation of lunettes as well as broader-scale aeolian erosion and sediment transport; drying and degradation of swamps and bogs including peats; and decreased active periglacial processes in the longer term.
- Increased frequency of landslides on TWWHA slopes is likely due to increased frequency of high intensity rainfall events.
- Increasingly seasonal runoff and stream flow variation in TWWHA fluvial systems are expected, with more frequent high intensity rainfall and flash-flood events interspersed with longer dry periods than in the past.
- Increased catchment and channel erosion and sediment deposition is likely in some locations due to these hydrological changes plus increased fire risk, moorland soil cover loss and other vegetation stresses in some areas.
- Increased degradation of organic soils generally is expected, including forest organic soils and sphagnum bog peats, due to increased warming, greater seasonal drying and increased fire risks.
- Increased flooding of low-lying coastal areas in response to sea-level rise is very likely, with increased instability, erosion and loss of existing soft coastal and estuarine sediment coastal landforms, and landwards migration of shorelines, coastal dunes and other active coastal landform systems.
- Increased seasonal water table and stream flow variation may occur in TWWHA karst systems, with some long term net drying of the Mole Creek karst being possible.
- More frequent flash flooding of caves is probable, with increased fluvial and landslide transport of sediments into caves in cases where increased catchment erosion and slope instability is occurring (see above).
- Long-term reduction of alpine freeze – thaw periglacial and nivation processes is expected, and degradation of deactivated periglacial landforms is likely (although some short-term freeze-thaw process increases are possible).
- Increased alpine aeolian process activity (wind erosion, sediment transport and deposition) may result in remobilisation of existing lunettes, expansion or formation of new alpine deflation features and lunettes, and broader scale aeolian erosion, transport and deposition generally (likely to be most marked on the Central Plateau). Dust or sand storms in and downwind of susceptible areas may become a more common phenomenon by 2100.
- Accelerated loss of some relict soft sediment deposits and landforms is expected in situations where these are exposed to accelerated erosion by changes in active processes resulting from climate change. Apart from the loss of the intrinsic value of these features, a key consequence for geoheritage values will be the loss of palaeo-environmental, stratigraphic and in some cases cultural information embodied by these features.
- In contrast, the wide variety of important geoheritage values embodied in the morphology or contents of hard-rock landforms and deposits are likely to be negligibly impacted by projected climate changes in most cases, although some small-scale hard-rock features may be at risk.

Position paper overview

The purpose of the position paper was to identify (insofar as is possible on current knowledge):

- the potential effects of projected climate changes on the geodiversity of the TWWHA;
- possible management responses to these risks; and to
- propose a framework for prioritising consideration of such management responses as may be possible and beneficial.

The analysis provided in the position paper was conducted in a systematic fashion as follows:

- Current projections of climate changes for Tasmania to 2100, as modelled by the 2010 Climate Futures Project conducted by ACE-CRC (Grose *et al.* 2010), are used as the basis for identifying potential effects on geodiversity, albeit noting that there are uncertainties associated with these projections.

- The elements of TWWHA geodiversity are examined in themes (types) which are grouped according to similarities in their dominant processes and *system controls*, that is, according to the environmental conditions (e.g., geology, topography, temperature, precipitation, vegetation dynamics, etc) that govern the nature and rates of their ongoing processes and development.

- The likely degree and nature of changes to the various geomorphic and soil *system controls* in the TWWHA that may result from climate changes are identified on the *assumption* that currently projected climate changes actually occur.

- The potential effects of these changed system controls on geodiversity are systematically identified by considering how each system control governs the nature and development of each geodiversity theme.

- The Australia – New Zealand Risk Management Standards (Standards Australia 2004) are adopted as a basis for prioritising consideration of management responses to identified potential impacts of climate change on TWWHA geodiversity. Potential impacts are prioritised according to their *likelihood* of occurring (assuming that climate changes occur more or less as currently projected) and their *consequences* if they occur (which are assessed specifically in terms of their consequences for continuing management ability to achieve the TWWHA Management Objectives as defined in the TWWHA Management Plan, PWS 1999).

Whilst this analysis takes into account known process feedbacks and change thresholds, it is acknowledged that there may be important unforeseen feedbacks and change thresholds affecting the response of geodiversity to climate change which this (systematic, reductionist) analysis cannot identify. However in most cases such additional processes will in any case only become apparent from future observations, monitoring and research - which are therefore highlighted as desirable activities in general.

It is of particular importance to note that the priorities identified by the process outlined above are not in the first instance priorities for *on-the-ground action* (e.g., mitigation, protection, monitoring, etc), but rather are priorities for *considering* whether any beneficial actions can be taken at all, and if so what. Many of the climate change impacts on geodiversity that are likely to occur in the TWWHA may be of such a scale and nature that little or nothing can (or indeed, should) be done to directly prevent or mitigate them. Nonetheless it is important to at least consider each potential impact – in a priority-based fashion – and to ask not only whether there are any mitigation actions that might be practicable and beneficial, but also whether there are any other actions that might be of benefit in other ways. Such other actions may include recording and archiving stratigraphic materials before they are destroyed by accelerated erosion, or monitoring inexorable changes so as to inform better understanding of and adaptation to those changes. Such activities might also be beneficial to other TWWHA values, for example understanding changes to geodiversity might contribute to identifying refugia for various vegetation communities and fauna as the climate changes.

Projected Climate Changes for the TWWHA

Climate variables are considered as affecting geodiversity at two distinct levels, namely:

1. As *Primary climate variables:* direct effects on geodiversity of changes in the primary climate variables, especially temperature, rainfall and wind (and associated climate variables such as effective precipitation, frost day frequency, etc);

and:

2. As *Consequential landscape process effects:* consequential effects on geodiversity of changes to landscape process drivers such as fire regime, sea-level and vegetation dynamics, which themselves will change in response to changes in the primary climatic variables.

It should be noted that changing distributions and numbers of faunal species and communities – many of which may also affect soil and geomorphic processes – can be considered a further consequential process effect of climate change resulting from vegetation changes and other climate-driven habitat changes; however this issue was not explicitly addressed in the report although it should be a focus for consideration in future.

In general, Tasmania and the TWWHA are projected to be less impacted by climate change to 2100 than most other parts of the world, due to Tasmania's maritime island climate which is moderated by the Southern Ocean, the slowest-warming ocean region on Earth. Nevertheless significant changes to these primary and consequential climate variables are expected, particularly in respect of changing regional and seasonal weather patterns within Tasmania.

Tasmania's mean temperatures were stable during the first half of the Twentieth century but have been rising since the 1950s. A continued rise in temperatures to 2100 is expected. As has been occurring since the 1950s, minimum temperatures are expected to rise more than maximum temperatures, resulting in fewer very cold or frost days. Although the projected patterns of mean temperature rise are relatively uniform across most of Tasmania, the Central Plateau (including TWWHA sections) is projected to warm notably more than the rest of Tasmania in all seasons, with the difference being most marked in winter and spring.

The TWWHA includes some of Tasmania's highest – rainfall regions. Although there has been a trend of reducing rainfall in Tasmania since 1975, this is not projected to continue and total annual rainfall over Tasmania is expected to remain within its historical range to 2100. At the same time however, evaporation is expected to increase in line with increasing temperatures leading to reduced effective precipitation and consequently to reduced runoff and stream flows. In addition, despite the limited changes to total rainfall over Tasmania as a whole, notable changes in spatial and seasonal rainfall patterns within Tasmania are expected over the next century. A steadily emerging pattern of decreasing total rainfall on the Central Plateau in all seasons together with increasing temperatures will lead to marked reductions in effective precipitation and stream flows in that region. On the west coast including much of the TWWHA a marked increase in winter and spring rainfall but a strong decrease in summer and autumn rainfall are expected, mainly after 2050. A decrease in snow cover is also anticipated in line with increasing temperatures. An increasing proportion of total rainfall is expected to occur in intense events (resulting in larger stream flooding events), with longer dry periods in-between.

Although average wind speeds across Tasmania are projected to decrease slightly, more complex spatial and seasonal patterns are expected to be super-imposed on this overall pattern. Average Tasmanian wind speeds by 2100 are projected to be higher than present in the windier July to October season, and generally lower than present during the quieter November to May period. Higher wind speed events than at present are expected to occur in association with more intense storm events. Southern and coastal parts of the TWWHA are expected to show slight increases in average wind speeds, while slight decreases in wind speed are expected in northern parts including the Central Plateau.

The projected combination of generally increased temperatures, wetter winters and springs (encouraging rapid spring plant fuel growth), and drier summers (encouraging faster summer drying of fuel), are expected to increase the potential severity of bushfires in the TWWHA over the period to 2100. In addition a changed pattern observed since the 1980's – that of an increased proportion of fires being caused by lightning strikes as compared to other causes - is expected to continue as a result of drier weather periods in summer, increased storminess and increased temperatures.

Vegetation dynamics in the TWWHA are likely to change with climate change, due to southerly and upwards migration of both native and introduced species, and the favouring of invasive weed species that have competitive advantages in the sorts of disturbance regimes expected to result from climate change. Many geomorphic and soil processes are strongly controlled by vegetation, and consequently may change as vegetation changes.

Ongoing sea-level rise, now projected to be between 1.0 and 2.0 metres above present levels by 2100, will have significant impacts on the microtidal coastal and estuarine environments in the TWWHA through increased coastal flooding, shoreline erosion and recession, and an upwards migration of coastal water tables with landwards penetration of saline groundwater (in a complex interaction with effective precipitation changes).

The fact that there are irreducible uncertainties in these climate change projections for the TWWHA, and that unexpected climatic outcomes could have unexpected impacts on TWWHA values including geoheritage, points to the desirability of adequate monitoring of climate and natural processes in the TWWHA in order to be able to detect deviations from currently projected changes and impacts.

The Geodiversity of the TWWHA

The geodiversity themes and elements of the TWWHA - and their geoheritage values - are considered in two broad groups, namely:

1. Active geomorphic and soils process systems (whose intrinsic and ecosystem values as ongoing processes with roles in broader ecosystem processes are particularly pertinent here). These have been broadly categorised according to the natural process 'system controls' governing their development and comprise active fluvial, mass movement, soil, coastal, karst, and alpine geomorphic process systems (some of which include sub-systems such as aeolian processes in the coastal and alpine themes);

   and:

2. Relict geological, landform and soil features (those formed in past environments by processes no longer active, and whose value for the evidence they preserve and expose of past environments and processes is particularly pertinent to this discussion, in addition to their intrinsic value and their roles in active ongoing processes). These include hard bedrock or soft sediment sequences preserving key fossil, mineral, sedimentary, stratigraphic, structural or other features; and relict glacial, karst, coastal and other landforms developed in both hard rock and soft sediment substrates. Relict features may range from very old Precambrian features to Late Holocene sediments or soils where the process regime may change from depositional to erosional.

The Sensitivity of TWWHA Geodiversity to Projected Climate Change

The sensitivity of TWWHA geodiversity to being impacted or changed by climate change has been analysed as follows:

1. For 'active process' geodiversity themes and elements, 'primary' and 'consequential' climate variables are considered as 'system controls' on geomorphic and soil processes. Hence this assessment first identifies the role that identifiable system controls (including but not only climate variables) play in driving each active geomorphic or soil process system, and then considers how each process system might change if its relevant climate system controls change more or less in accordance with current Climate Futures projections (Grose *et al.* 2010).

2. For 'relict' geodiversity themes and elements, the approach adopted in the report was to consider which currently active geomorphic or soil process systems the relict features are exposed to or part of, and to consider whether changes to those active processes might be such as to accelerate any potential for degradation (or indeed enhancement such as through increased exposure) of the geoheritage values of the relict features.

Based on this approach, Table 1 below (Table 5, Section 7.1 of the full report) provides a full listing of identified potential impacts of projected climate changes on TWWHA geodiversity. Key highlights include:

- *Moorland organic soils degradation (particularly on slopes)*: The combination of warmer, drier summer conditions and increased risk of intense fires means that moorland organic soils in the TWWHA – especially those on steeper, better drained slopes or on freely-draining substrates including porous gravels and sand – are likely to be at increased risk of degradation or destruction through desiccation, oxidation and burning. Considering the large area of the TWWHA mantled by these soils, the fact that they are already at their climatic limit, and the broad consequences for fluvial, mass movement and other geomorphic processes, as well as habitats, aesthetics and other TWWHA values if large areas of these soils are significantly degraded, this potential impact stands out as having possibly the most pervasive implications of any identified potential impacts of climate change on TWWHA geodiversity (Section 4.2.4 of the full report).

- *Increased drying, wind and water erosion of Central Plateau mineral and organic soils and sediments*: The Central Plateau stands out in comparison to other parts of the TWWHA as the region where the largest climatic changes are projected by 2100. Greater warming (including fewer frost days) and lower rainfall, runoff and stream flows are projected in all seasons by 2100. Thus it is an area projected to be significantly warmer and drier overall, not merely on a seasonal basis as is the case for other parts of the TWWHA (Sections 4.2.2, 4.2.4, 4.2.7 of the full report). Runoff, fluvial, lacustrine and palludal (swamp or bog) processes are likely to change significantly. Areas subject to active periglacial processes (e.g., patterned ground and frost shattering) are likely to decrease in the long term although there may be short term intensification of some freeze-thaw processes (Section 4.2.7 of the full report). Increased susceptibility to erosion of organic and mineral soils, lunettes and other sediments including bog peats is likely due to drying, vegetation stress and dieback plus increased fire risk, although possibly countervailing factors include decreased exposure to agents of fluvial erosion (due to decreased runoff), wind erosion (decreased windiness) and frost heave (fewer frosty days). Nonetheless increased erosion and sediment transport (by both water and wind) is likely to be the net outcome, mainly due to the likely extent of vegetation loss and to more intense storm events, although the countervailing factors mean that unforeseen feedbacks may occur and result in unexpected outcomes in some cases.

- *Increased frequency of mass movement events*: Landslides including block-falls, block-slides, slumps and debris flows currently occur naturally in the TWWHA as part of ongoing landscape evolution processes, however the projected increase in frequency of intense rainfall events means these events are likely to occur more frequently and more widely in future. Although they may occur on well-forested slopes where susceptible substrates are present, projected increases in bushfire frequency will also exacerbate the frequency of mass movement events due to vegetation cover destruction. More frequent landslides have the potential to impact significantly on fluvial and karst processes, in particular by supplying large quantities of sediment into streams and in some cases thereby diverting watercourses (Section 4.2.3 of the full report).

- *Changes to fluvial processes*: More seasonally variable catchment runoff and stream flows (including increased flood frequencies, generally higher-than-present winter discharges and reduced summer base flows) are expected. With associated increased catchment and riparian vegetation and soil stress due to drying and fires, this may lead to increased catchment, channel and lake outlet erosion in soft substrates, with associated increased sediment transport and deposition, and potentially more frequent river channel avulsions (Section 4.2.2 of the full report). Fluvial catchments dominated by moorland organic soils subject to degradation –

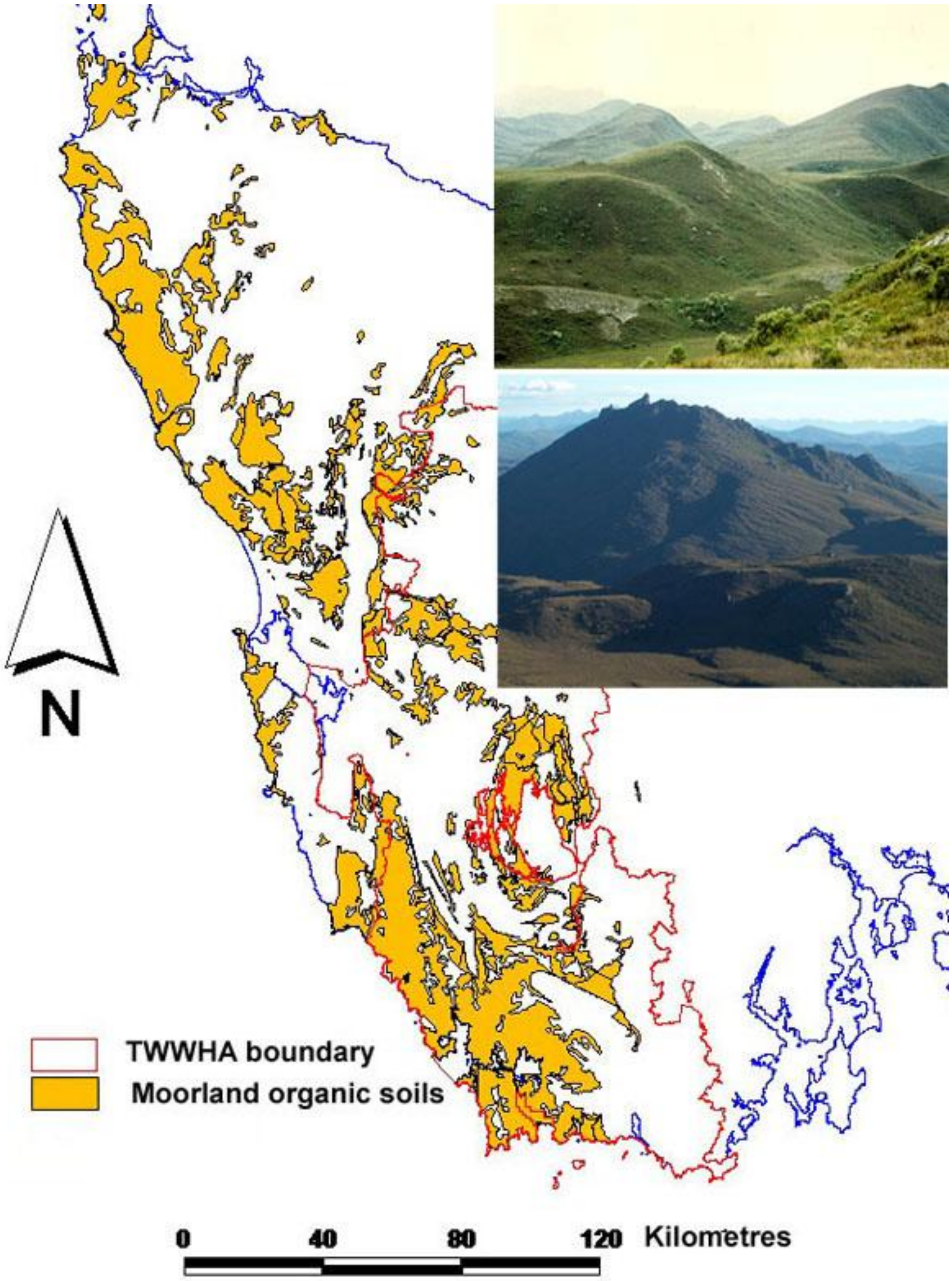

Figure 1: Map showing approximate extent of moorland organic soils in the TWWHA and elsewhere in western Tasmania. Inset photos provide examples of moorland vegetation / organic soil terrain in the TWWHA, showing both steep slopes and valley floors occupied by this vegetation type. Note that the depiction of organic soil extent on this map is incomplete. Given the large portion of the TWWHA dominated by these soils, it is clear than any substantial degradation or loss of these soils would have implications for a wide range of TWWHA processes and values. Photos by Chris Sharples

especially on slopes with colluvial or other unlithified sediment currently stabilised by the organic soils – are likely to undergo significant fluvial process and landform changes including increased runoff, slope sediment erosion and downstream deposition (Sections 4.2.2, 4.2.4 of the full report).

- *Soil degradation*: TWWHA soils will be prone to generally increased but patchy degradation and erosion by more frequent intense rainfall and wind storm events as a result of increased vegetation stress resulting from seasonal drying - and loss from increased firing - leading to more soil exposure and increased slope mass movements. The impacts will be widely variable depending on local situations, however organic soils generally (including forest organic soils and sphagnum bog peats) will be more at risk than mineral soils owing to their greater sensitivity to warming and drying which may cause desiccation and oxidation, and to fires (Section 4.2.4 of the full report).

- *Coastal process changes*: Erosion of open coast sandy beaches and dunes, and 'sheltered' re-entrant and estuarine shores including 'marsupial lawn' and soft sandstone shores, is already widely in progress in the TWWHA and is likely to be at least partly a response to sea-level rise which has already occurred to date; these processes will accelerate with continuing sea-level rise resulting in a more unstable coast into the foreseeable future (i.e., for as long as sea-level rise continues). Accompanying increased coastal mean and storm water levels and flooding will become increasingly significant by 2100, together with rising coastal groundwater tables. The rates, magnitudes and styles of change will not necessarily be comparable to those which occurred during previous Pleistocene sea-level changes since the underlying (anthropogenic) causes are not the same this time. Although coastal landform systems will continue to exist, some permanent losses of geoheritage and cultural values are inevitable, including specific coastal landforms such as currently existing spits and dunes, their contained Holocene and Pleistocene stratigraphic and palaeo-environmental information, middens and other values that will be lost from eroded soft sediment or soft rock coastal features (Section 4.2.5 of the full report).

- *Karst process changes*: Likely downstream effects of projected climate change impacts on fluvial and mass movement processes include increased flash flooding of caves, more frequent associated catchment landslides supplying coarse sediment to caves, and increased transport of sediment into caves from catchments eroding due to fire and other vegetation stresses. Notable events of these types have already impacted on caves at Mole Creek and the nearby Gunns Plains karst in recent years (Section 4.2.6 of the full report). Changes to karst water chemistry are possible but of unclear magnitude, however notably increased seasonal variation in water availability (including cave stream flows and water table levels) is likely to affect all TWWHA karst systems. Some net long term drying may affect the Mole Creek karst but may not be noticeable in other TWWHA karsts. A landwards shift in the focus of coastal karst processes is likely to occur in coastal and estuarine karsts due to sea-level rise (Section 4.2.5, 4.2.6 of the full report).

- *Long-term reduction of alpine freeze – thaw periglacial and nivation processes, and degradation of deactivated periglacial landforms (short-term freeze-thaw process increases possible):* Generally warmer temperatures, reduced snowfall and reduced frost days are likely to inhibit rock-splitting due to ice-wedging, and reduce ongoing formation of patterned ground, solifluction terraces, nivation hollows and some forms of alpine scree. As the active periglacial processes maintaining these landforms cease, some may be degraded by wind and water erosion (Section 4.2.7 of the full report). However some countervailing processes (including more bare alpine soil exposed to freeze-thaw processes due to vegetation loss, and more overnight freeze-thaw cycling as winter minimum temperatures initially rise slightly) mean that the intensity of some freeze-thaw periglacial processes could increase up to a certain point, until they are overwhelmed by the general warming trend (see Section 4.2.7 of the full report).

- *Increased alpine aeolian process activity (especially on the Central Plateau)*: Despite generally negligible increases and some decreases in mean wind speeds, increased aeolian (wind) erosion, sediment transport and deposition is likely in alpine areas due to increased vegetation loss and soil exposure through drying and fires, and more frequent intense storm winds (Section 4.2.7 of the full report). This is likely to be most marked on the Central Plateau due to greater drying there, and may result in broad-scale aeolian erosion and sediment transport as well as - more specifically - destruction and re-mobilisation of some existing lunettes (with consequent loss of contained stratigraphy and palaeo-environmental information), likely formation of new active deflation hollows and lunettes, and possible expansion of some fjeldmark areas. Dust or sand storms in and downwind of susceptible areas may become a more common phenomenon by 2100 (previously rare in Tasmania).

Figure 2: Slopes to the west of Hardwood River (TWWHA) denuded of moorland organic soils following intense fires. Given current climate change projections for the TWWHA (Grose *et al.* 2010), there is potential for this type of organic soil loss – which has already occurred in some areas of Western Tasmania due to intense fires during the 19th and 20th Centuries – to become more widespread and irreversible. Photo by Michael Comfort.

Figure 3: Actively eroding and receding 'Marsupial Lawn' organic soil shores such as those shown here at Horseshoe Inlet (Bathurst Channel area), are now estimated to be more widespread on TWWHA shorelines than accreting or stable Marsupial Lawn shores. This is suggestive of a trend towards recession consistent with the expected response of these 'sheltered' shores to sea-level rise. Nonetheless these organic soil–vegetation associations are capable of accreting when conditions permit, and may persist by migrating landwards as sea level rises. Photo by Chris Sharples.

- *Accelerated loss of some relict soft sediment deposits and landforms:* In some situations the climate change effects on active geomorphic processes identified above are likely to result in increased erosion of a wide variety of relict landforms and deposits composed of unlithified sediment or soft deeply weathered materials. In such cases there may be significant losses of geoheritage embodied in the intrinsic value of these features, as well as the loss of scientific and cultural information expressed by ancient landform morphologies or contained in the stratigraphy and palaeo-environmental information (including fossils and cultural deposits) within the soft erodible materials. Soft relict geoheritage will vary widely in its susceptibility to degradation resulting from climate change, depending on factors including inherent sensitivity, degree of exposure to changing processes and the extent of the significant features; however some significant losses are likely. Examples at risk of partial or total degradation include:

    - Holocene and Pleistocene stratigraphies and Aboriginal cultural materials contained within TWWHA coastal dunes (already in the process of being destroyed by coastal erosion and recession caused by rising sea levels).
    - Palaeo-environmental information in Mid-Holocene lunette forms and stratigraphic contents on the Central Plateau (at risk of erosion due to vegetation cover loss and increasingly active alpine aeolian processes).
    - Holocene fluvial stratigraphies preserved in floodplain sediments may be increasingly scoured out and lost in river systems experiencing increased rates and magnitudes of fluvial channel erosion and meander migration.
    - Erosional degradation of outstanding fluvial terrace morphologies cut in Tertiary-age gravels stabilised by moorland organic soils in the Sorell River region, and erosion of well-expressed Pleistocene (Last Glacial) moraine and alluvial fan morphologies preserved by slope moorland organic soil covers in various south-west TWWHA locations (due to potential degradation of organic soils on slopes).
    - Potential loss of Pleistocene glacial and glacio-fluvial sediment stratigraphies (due to increased fluvial channel erosion during increasingly intense flash flood events).
    - Reworking of Quaternary cave fills containing valuable stratigraphic and fossil information (by increasing flash-flood events in caves).
    - Sphagnum peat bog deposits with contained palaeo-environmental records.

- *Generally negligible losses of relict hard-rock landforms and contents*: In contrast, the wide variety of important geoheritage values embodied in the *morphology* of hard-rock landforms such as hard-rock glacial landforms and structural landforms, and in the *content* of hard bedrock exposures and deposits, including stratigraphic and palaeo-environmental information, fossils, minerals and geological structures, are likely to be negligibly impacted by projected climate changes in most cases, although some small-scale hard rock features may be at risk. Reduced periglacial process activity in alpine areas may even reduce the current rate of erosion of alpine hard rock glacial and periglacial landforms by ice-shattering and related mechanical weathering processes.

It should be noted that the position paper documents a strictly 'first - pass' assessment of what potential impacts on or changes to geodiversity in the TWWHA *could* occur, in principle, given the types of climate changes projected and the types of climatically – influenced system controls that govern geomorphic and soil processes in the TWWHA. However whether such effects on or changes to geodiversity in the TWWHA *do in fact* occur at some time between now and 2100 will depend on a range of processes, thresholds and feedbacks which in some cases are poorly understood and which in all cases were beyond the scope of this 'first pass' to investigate.

Figure 4: Regularly spaced vegetation – bound gravel terraces such as these well-developed examples on The Boomerang (TWWHA) are an example of an active periglacial process that is likely to become restricted to smaller, higher alpine areas in the TWWHA because of general warming, and which could be destroyed if increased fire frequencies destroy the binding vegetation. Photo by Chris Sharples.

Figure 5: The far southwest coast of the TWWHA (seen here at Window Pane Bay just north of the southwest tip of Tasmania) has the most energetic and stormy wave climate of any Australian coast and this fact is an important system control determining both past and ongoing behaviour of TWWHA coastal landforms. The dune erosion seen here is widespread on TWWHA coasts and is consistent with the expected response of these shores to the sea-level rise that has already occurred to date. Photo by Chris Sharples

Possible Management Responses to Climate Change Risks and Impacts on Geodiversity in the TWWHA

The view adopted in the position paper is that some degree of changes to geodiversity in the TWWHA is likely to occur, albeit of widely varying magnitudes. It is in general unlikely to be beneficial (in terms of the TWWHA management objectives) to attempt to prevent or significantly mitigate those impacts because of the large (global) scale of the driving processes, the likely huge expense of the 'geo-engineering' that would be required, and in particular the probability that such interventions would compromise other natural TWWHA processes and values. In effect, the natural systems of the TWWHA will evolve in response to climate change, and since a significant degree of global climate change is now 'locked in' there seems little point or justification in attempting to prevent this. Given this, it is evident that the goal of management in the TWWHA should be to *manage the consequences of change* rather than to attempt to stop it happening.

From this perspective, four fundamental management response options to potential impacts on TWWHA geodiversity can be identified (see Section 6.2 of the full report), namely:

1. *Do Nothing*:
   It is likely that in many cases the only realistic response to climate change impacts in the TWWHA will be to do nothing other than observe changes and perhaps modify any relevant parks infrastructure or procedures as necessary.

   However there may be circumstances in which some limited responses of a more concrete sort may be useful or justifiable, as indicated below:

2. *Recording, sampling and preserving information likely to be lost*:
   In cases where climate change is resulting in complete loss (e.g., through accelerated erosion) of features containing irreplaceable stratigraphic, palaeo-environmental, cultural or other information, it may be appropriate to record site information and collect representative samples for future study, reference or display. An example is coastal dunes containing palaeosols, middens and other stratigraphic information which are eroding in response to sea-level rise. It is impractical to preserve these dunes without enormous expense and interference with TWWHA natural processes, and indeed similar coastal geomorphic process systems will ultimately re-establish further to landwards following a period of instability. However these will be new dunes, and much of the palaeo-environmental and cultural history (e.g., middens) contained in the former dunes will be destroyed (albeit some will simply be buried).

3. *Monitoring and researching climate change impacts on geodiversity*:
   Monitoring of and research into the rates and manner of changes to geodiversity in the TWWHA in response to climate change may be worthwhile in cases where:

   - monitoring may be useful in identifying opportunities for beneficial limited interventions into TWWHA geo-processes;

     or where:

   - better understanding of change processes in geodiversity may assist in planning management responses to changes in dependant values within the TWWHA (e.g., understanding how habitats are changing and identification of refugia);

     or where:

   - the improved understanding is beneficial for planning adaptation to similar changes outside the TWWHA (for example studies of coastal recession on TWWHA beaches is likely to contribute to predicting sandy shoreline recession rates in south-eastern Australia generally).

An additional benefit of monitoring and research is that this may enable earlier detection of un-anticipated feedback processes and departures from projected rates and magnitudes of geo-process change in response to climate change.

4. *Selective limited intervention to mitigate projected impacts on geodiversity*:
Whilst it is in general unlikely to be beneficial (in terms of the TWWHA management objectives) to attempt to prevent or significantly mitigate impacts on geodiversity in the TWWHA in response to climate change, limited or selective interventions such as changed fire management regimes, or the protection or relocation of some specific features, may in some cases be practical and beneficial. Cases where such interventions may be worthwhile include:

    - where it is possible to slow (even if not prevent) an inevitable change (e.g., loss of organic moorland soils); this may be worthwhile because:

        - slower changes may be less disruptive to other natural and human systems;

          or because:

        - intervention might reduce the total end change that would otherwise have occurred;

      or if:

    - a potentially large and catastrophic change is critically sensitive to initial conditions, which can be modified by influencing something manageable to produce a less drastic outcome.

Prioritisation of Management Responses to Climate Change Risks and Impacts on Geodiversity in the TWWHA

Using the Australia – New Zealand Risk Management Standard as a framework (Standards Australia 2004), the identified potential impacts of climate change on geodiversity in the TWWHA have been prioritised according to their *likelihood* of occurrence by 2100 (assuming currently projected climate changes actually occur) and their *consequences* if they do occur (for continuing management ability to achieve the TWWHA Management Objectives as defined in the TWWHA Management Plan). The resulting prioritised list is provided as Table 1 (Table 5 in Section 7.1 in the full report). The highest priority issues identified on Table 1 are included in the TWWHA geodiversity sensitivity highlights summarised above.

Prioritised consideration of the identified potential impacts of climate change on geodiversity in the TWWHA should focus on:

- whether the potential impacts are indeed credible risks; and

- if so, whether any achievable on-ground management actions (including recording, monitoring and research or limited interventions) would be beneficial in terms of the TWWHA Management Objectives, and if so what actions could or should be implemented.

Ongoing Review

Given the current uncertainties in climate modelling, natural process responses to climate change and unpredictable feedbacks that may occur, it is strongly recommended that this assessment should be subject to continuing review and periodic re-assessment as knowledge and understanding of climate change processes and impacts on the TWWHA continues to grow.

Table 1: Risk priority levels assigned to specific potential impacts of climate change on TWWHA geodiversity by 2100, as identified in Sharples (2011). Note that many of the impacts listed are inter-related; however where similar impacts are listed more than once the intention is to identify differing implications. Section numbers cited in this table refer to the full report (Sharples 2011), in which this table is presented as Table 5.

	Priority Level	**Extreme**
Extreme	**Criteria**	Urgent need to consider and decide on the most appropriate response (if any), demanding urgent attention at the most senior relevant management levels. This priority level requires urgent – not routine – consideration and decisions.
Extreme	**Potential Impacts**	**Rationale for priority level**
Extreme	*Moorland organic soils degradation*; Warmer temperatures and drier summers may cause more frequent summer drying of moorland organic soils, especially in (already marginal) better-drained situations (especially slopes). Likely consequent reduction in organic soil accumulation rates (or switches to oxidation, desiccation and net degradation), combined with higher risks of summer bushfires generally, could lead to significant widespread loss of organic soils. Because topography and drainage are key factors, it is likely that moorland organic soils on better-draining slopes will be impacted faster and to a greater degree than those in poorly-drained valley-bottoms (Sections 4.2.4).	Likely, consequences catastrophic (potential total irreversible loss of organic soils from extensive areas of better-drained slopes at least, with widespread consequent effects likely on slope, fluvial and other geomorphic processes, soft sediment landform morphologies and deposits (landform contents), and biological communities and aesthetic values).
Extreme	*Increased drying, wind and water erosion of Central Plateau mineral and organic soils and sediments*: Increased regional warming and drying at all seasons is likely to change runoff, fluvial, lacustrine and palludal (swamp or bog) processes significantly. Greater susceptibility to erosion of organic and mineral soils and sediments is likely due to vegetation stress and dieback plus increased fire risk, however possibly countervailing factors include decreased exposure to agents of fluvial erosion (due to decreased runoff), wind erosion (decreased average windiness) and frost heave (fewer frosty days in the longer term). However the net outcome is most likely to be widespread increased erosion (including wind erosion) of alpine soils, swamps or bogs, lunettes and other sediments, mainly due to the likely extent of vegetation loss and to intense storm events, although the countervailing factors mean that unforeseen feedbacks may occur and could result in unexpected outcomes in some cases (Sections 4.2.2, 4.2.4, 4.2.7). See also "Increased alpine aeolian process activity" below.	Almost certain (all climate models indicate the most significant primary climatic variable changes for the TWWHA will be in the Central Plateau region); major consequences (widespread drying and increased net wind and water erosion most likely, with pervasive flow-on consequences for fluvial, lacustrine, palludal, slope, periglacial, aeolian and other processes, soft sediment landform morphologies and deposits (landform contents), and biological communities and aesthetic values).

Table 1. continues next page.

	Priority Level	**High**
High	**Criteria**	High priority to consider and determine appropriate response in the course of routine operations. Final decisions on appropriate responses to these risks will be the responsibility of the most senior relevant management levels.

Potential Impacts	**Rationale for priority level**
Fluvial and lacustrine geomorphic process and landform changes: More seasonally variable catchment runoff and stream flows (including more frequent intense rainfall, high runoff and flood events, generally higher-than-present winter discharges and reduced summer base flows) are expected. With associated increased catchment and riparian vegetation and soil stress due to drying and fires, this may lead to increased catchment, channel and lake outlet erosion in soft substrates, with associated increased sediment transport and deposition, and potentially more frequent river channel avulsions (Sections 4.2.2).	Likely, moderate consequences (impacts likely to be spatially and temporally variable depending on events and local conditions, ranging from little change in some situations such as hard-rock channels or lake basins and intact forested catchments; to substantial changes in others such as soft-substrate channels, vegetation-stressed catchments, and moorland organic soil catchments and channels).
Fluvial geomorphic landform and process degradation in moorland organic soil catchments: Fluvial catchments dominated by moorland organic soils subject to degradation – especially on slopes with colluvial or other unlithified sediment currently stabilised by the organic soils – are likely to undergo significant fluvial process and landform changes including increased runoff, slope sediment erosion and downstream deposition (Sections 4.2.2, 4.2.4).	Possible, consequences catastrophic (major irreversible landform and process changes in susceptible regions as organic soils lost from slopes and elsewhere).
Erosion and landwards migration of estuarine deposits, marshes and landforms including lakes: General landwards and upstream migration of estuarine features is an expected geomorphic response to sea-level rise; of particular note is that estuarine lake morphologies, chemistry and stratification are likely to be destroyed by sea-level rise (Sections 4.2.2, 4.2.5).	Likely, major consequences (estuarine landforms, processes, and biota including unusual or unique estuarine lakes of significant geoheritage and limnological value (e.g., Gordon River meromictic lakes) may be entirely lost in the medium term, albeit equivalent features including new lakes might form further landwards up estuaries in the future).
Potential acidification of episodically – drying swamps: potentially serious impact related to increased episodic drying-out of button-grass swamps and similar, allowing oxidation of formerly waterlogged acid sulphate soils; however it is unclear how severe this problem could be in the TWWHA (Section 4.2.2).	Possible, major consequences (potentially major changes to TWWHA swamp chemistry and ecosystems with impacts on dependant values including biota and ambience).
Increased incidence of terrestrial slope mass movement events: Block-falls and slides, rotational slumps, debris flows and other landslips are likely to occur more frequently in susceptible slope materials in response to more frequent intense precipitation events, especially but not only where fire causes more frequent vegetation losses, or vegetation types change in response to changing primary climate variables (Section 4.2.3).	Likely, moderate consequences (likely to remain localised occurrences, but may be more locally extensive and frequent in susceptible situations than at present; may have major localised consequences when fluvial catchments are destabilised or drainages are diverted (see Section 4.2.2), or where landslips impact on cave systems (see also Section 4.2.6).

Table 1. continues next page.

Priority Level	**High (continued)**	
Criteria	High priority to consider and determine appropriate response in the course of routine operations. Final decisions on appropriate responses to these risks will be the responsibility of the most senior relevant management levels.	
High	**Potential Impacts**	**Rationale for priority level**
	Increased degradation and erosion of organic soils and peats generally: Forest organic soils, sphagnum bog peats and other organic soils generally are at higher risk (than mineral soils) of reduced or nil accumulation, degradation and erosion due to warming, seasonally increased drying and increased fire risk (Section 4.2.4).	Likely, moderate to major consequences (organic soils are generally at higher risk than mineral soils because they are more susceptible to reduced or nil accumulation, desiccation, burning and erosion resulting from expected warming, seasonally increased drying and increased fire risk; however only the moorland organic soils sub-type are given 'extreme' risk priority (above) because they are areally most extensive and contiguous with more pervasive flow-on consequences likely compared to other organic soil types which are hence rated 'high' priority only.
	Increased erosion and mobility of coastal dunes: Already in progress along TWWHA coast and expected to accelerate with ongoing shoreline erosion due to sea-level rise and projected increasing wind speeds on TWWHA coast (Sections 4.2.4, 4.2.5).	Erosion almost certain (increased mobility possible), moderate consequences (process changes comparable to natural changes in the past and of minor consequence for TWWHA geomorphic processes, however valuable stratigraphic and palaeo-environmental information in current dunes will be irreversibly and widely lost, along with other dependant values including middens).
	Increased flash-flooding of caves with increased sediment deposition or reworking: More frequent flooding of caves in high rainfall events is likely; if catchment erosion is increasing (Section 4.2.2) sediment may be transported into caves and deposited, if not then existing cave sediments may be reworked or lost (Section 4.2.6). Increased potential for landslips in karst catchments (Section 4.2.3) may have significant impacts on caves, resulting in diverted watercourses, and increased sediment supply to caves in flood waters, and in some cases slumping of colluvial sediments directly into caves.	Likely, moderate consequences (process changes comparable to natural changes in the past, however reworking or loss of existing sediments in some caves may result in loss of valuable stratigraphic and palaeo-environmental information). Impacts on show cave infrastructure likely (and some have already occurred in response to recent flooding events at Mole Creek and Gunn's Plains Caves).

Table 1. continues next page.

	Priority Level	**High (continued)**
	Criteria	High priority to consider and determine appropriate response in the course of routine operations. Final decisions on appropriate responses to these risks will be the responsibility of the most senior relevant management levels.
	Potential Impacts	**Rationale for priority level**
High	*Long-term reduction of alpine freeze – thaw periglacial and nivation processes, and degradation of deactivated periglacial landforms (short-term freeze-thaw process increases possible):* Generally warmer temperatures, reduced snowfall and reduced frost days are likely to inhibit rock-splitting due to ice-wedging, and reduce ongoing formation of patterned ground, solifluction terraces, nivation hollows and some forms of alpine scree. As the active periglacial processes maintaining these landforms cease, some may be degraded by wind and water erosion (Section 4.2.7). However some countervailing processes (including more bare alpine soil exposed to freeze-thaw processes due to vegetation loss, and more overnight freeze-thaw cycling as winter minimum temperatures initially rise slightly) mean that the intensity of some freeze-thaw periglacial processes could increase up to a certain point, until they are overwhelmed by the general warming trend (see Section 4.2.7).	Possible, major consequences for geoheritage (partial or potentially total cessation of active periglacial process geodiversity, and subsequent loss of mainly small-scale active periglacial landform geoheritage to wind and water erosion over significant parts of current alpine areas, especially the Central Plateau).
	Increased alpine aeolian process activity (especially on the Central Plateau): Despite generally negligible increases and some decreases in mean wind speeds, increased aeolian (wind) erosion, sediment transport and deposition is likely in alpine areas due to increased vegetation loss and soil exposure through drying and fires, and more frequent intense storm winds (Sections 4.2.7). This is likely to be most marked on the Central Plateau due to greater drying and vegetation stress there, and may result in destruction and re-mobilisation of some existing lunettes and other aeolian deposits (with consequent loss of contained stratigraphy and palaeo-environmental information), likely formation of new active deflation hollows, lunettes and other aeolian deposits; and possible expansion of some fjeldmark areas. Dust or sand storms in and downwind of susceptible areas may become a more common phenomenon by 2100 (previously rare in Tasmania). See also "Increased drying, wind and water erosion of Central Plateau mineral and organic soils and sediments" above.	Possible, major consequences for geoheritage and alpine ecosystems (potential loss of existing alpine lunettes and contained stratigraphy, expansion of more arid alpine ecosystem processes).
	Degradation (mainly erosion) of relict soft – sediment geoheritage (soft-landform morphologies and sediment contents): Some degradation of a wide range of relict soft-sediment geoheritage features will probably occur in response to changing fluvial and catchment erosion processes, loss of binding organic soils, increased mass movement, accelerated coastal erosion and other changes to active processes. Examples of potential losses include the forms and contents of Holocene and Pleistocene coastal dunes and terrestrial lunettes; erosional degradation of the forms of river terraces cut in older soft sediments due to loss of binding organic soils (e.g., Sorell River terraces); loss of important Pleistocene glacio-fluvial deposits in widening river channel banks; increased degradation of steep Last Glacial moraine forms by increased organic soil loss with consequent gully erosion together with increased side-slope slumping of till; and loss of peat bog sediments and palaeo-environmental records (Sections 4.3.2, 4.3.3).	Likely, moderate consequences (some significant instances of degradation and loss will probably occur, and will be most significant if key stratigraphic and morphological records of past processes and palaeo-environmental history are lost. However the degree, importance and imminence of impacts are likely to be highly variable depending on inherent susceptibility, exposure, extent and other factors governing particular cases and though significant coastal sediment deposits may be eroded, others may usefully become more exposed).

Table 1. continues next page.

	Priority Level	Medium
Medium	**Criteria**	Consideration and determination of appropriate responses to these risks will be needed as a medium-priority part of routine operations, but they will be explicitly assigned to relevant officers to keep under review, and reported on to senior relevant management levels.
	Potential Impacts	**Rationale for priority level**
	Changes to lake hydrologies: Water temperatures, chemistry, stratification and biota may be affected by changing winter and summer through-flow rates relating to changing seasonality of effective precipitation (Sections 4.2.2).	Possible, consequences moderate (likely some lakes will show minimal changes, others may be more significantly changed; see Section 4.2.2).
	Generally increased mineral soil erosion hazard: Widespread increased mineral soil erosion likely due to vegetation stress, increased exposure from fires and increased mass movement; however degradation risks likely to be patchy and variable depending on local situations (Sections 4.2.4).	Possible, consequences moderate (widespread but sporadic soil erosion increases likely).
	Increased coastal and estuarine flooding: Progressively rising mean and storm water levels and inundation with sea-level rise, potentially increased in estuaries with coincident increased river flooding (Sections 4.2.2, 4.2.5).	Almost certain, minor consequences (little infrastructure at risk in TWWHA, coastal landforms and ecosystems expected to migrate landwards as has occurred during previous Pleistocene sea-level changes).
	Increased erosion and recession of sandy open coast beaches: Already in progress along TWWHA coast and expected to accelerate with ongoing sea-level rise (Sections 4.2.5). See also "Increased erosion and mobility of coastal dunes" above.	Almost certain, minor consequences (process changes comparable to natural changes in the past and probably of insignificant consequence for TWWHA geomorphic processes; beaches mostly backed by low sediment - infilled terrain and have capacity to migrate landwards as sea-level rises).
	Increased coastal rock-falls, scree and talus activity, and slumping in susceptible rocky coastal terrains including cliffs and steep slopes: Expected to accelerate with ongoing sea-level rise permitting more frequent higher – level wave attack, together with the triggering effects of more frequent intense rainfall events saturating over-steepened or under-cut coastal slopes and cliffs (Sections 4.2.3, 4.2.5).	Likely to occur, minor consequences (process changes comparable to natural changes in the past and probably of insignificant consequence for TWWHA geomorphic processes generally, losses of valuable stratigraphic and palaeo-environmental information likely to be minimal).
	Erosion and landwards migration of 'soft rock' and 'Marsupial Lawn' and other soft littoral soils on re-entrant and estuarine TWWHA shores: Already in progress in Port Davey – Bathurst Harbour and Macquarie Harbour areas and expected to accelerate with ongoing sea-level rise and potentially with increased wind speed in SW coastal areas causing increased local fetch-generated wave exposure (Sections 4.2.4, 4.2.5).	Almost certain, probably minor consequences (unique soil-plant associations, which however should be able to migrate and re-establish to landwards; generally few other dependant values at risk).

Table 1. continues next page.

Priority Level	**Medium (continued)**	
Criteria	Consideration and determination of appropriate responses to these risks will be needed as a medium-priority part of routine operations, but they will be explicitly assigned to relevant officers to keep under review, and reported on to senior relevant management levels.	
Medium	**Potential Impacts**	**Rationale for priority level**
	Rising coastal water tables and landwards penetration of saline groundwater wedge: Probably already in progress and likely to continue with sea-level rise; however nature and extent of changes also depend on changes to effective precipitation and infiltration (Section 4.2.5).	Likely, probably minor consequences (likely to cause dieback of littoral vegetation, however most affected communities are expected to migrate landwards and re-establish).
	Increased sediment supply to coast from rivers: Possible result of increased catchment and river channel erosion and increased river flooding (Sections 4.2.2, 4.2.4). Increased sediment supply could result in accretion of bars and beaches in some locations (Section 4.2.5).	Possible, probably minor consequences (may slightly offset coastal erosion processes in some locations).
	Changes to karst water chemistry causing changes to limestone, dolomite and speleothem dissolution or precipitation rates: More acid rainfall and soil temperature increases leading to increased biological activity and raised soil CO_2 may increase acidity of percolating ground waters causing increased dissolution; however limestone solubility will also be less with increased water temperatures, and potential loss of organic soils (Section 4.2.4) may reduce availability of humic acids in karst waters, hence net outcomes are uncertain and may be minor (Section 4.2.6).	Possible, minor consequences likely (some changes to limestone, dolomite and speleothem dissolution / precipitation rates are possible; however countervailing factors mean outcomes unclear, minor changes likely).
	Some net drying, and generally increased seasonal variability of moisture levels in karst and caves (streams, water tables, groundwater, humidity): Net long-term drying is likely in some but not all TWWHA karsts (most notably Mole Creek), although the degree of drying is uncertain and may turn out to be minor. However significantly increased seasonal variability in moisture levels within TWWHA caves generally is likely, which may influence water tables and cave stream flows, stress aquatic cave fauna and impact on speleothems; however the overall scale of impacts is unclear. An additional factor whose potential impact is currently difficult to assess is the effect of climate-driven changes to vegetation types in karst catchments (Section 2.3.3), which may affect groundwater moisture percolation and water tables due to changing vegetation water demands. Shallow entrance zone processes and biota are likely to be more affected than deep cave environments (Section 4.2.6).	Possible, moderate consequences may occur (probably within range of past natural process changes, minor but probably not major long term net drying expected in some karsts. However increased seasonal variability may cause some losses of dependant values including stressed aquatic cave fauna).
	Direct impacts of increased firing on karst: Projected increased fire risk in the TWWHA (Section 2.3.2) may have direct local impacts on karst systems include cracking, spalling and calcination of limestone surfaces. Changed groundwater infiltration rates and chemistry due to vegetation cover loss may in turn cause soil slumps in sinkholes or above caves, and affect dissolution and speleothem precipitation rates within underlying caves (Section 4.2.6).	Possible, minor consequences (likely to be sporadic impacts rather than widespread).

Table 1. continues next page.

Medium	**Priority Level**	**Medium** (continued)
	Criteria	Consideration and determination of appropriate responses to these risks will be needed as a medium-priority part of routine operations, but they will be explicitly assigned to relevant officers to keep under review, and reported on to senior relevant management levels.
	Potential Impacts	**Rationale for priority level**
	Landwards migration of coastal karst processes: Sea-level rise (Section 2.3.4) will raise coastal and estuarine karst process base levels and cause marine waters to affect these karsts further to landwards than previously, changing the focus of aggressive mixing corrosion processes over a lateral range which will be generally small for open coast karsts, but may be more significant for estuarine and lagoonal limestone karsts along the Lower Gordon River and in New River Lagoon. This will shift the focus of the most active dissolution processes to landwards, and possibly even result in initiation of new karstic conduits, albeit the effective magnitude of such process changes is unclear (Section 4.2.6).	Likely, minor consequences (comparable changes have occurred repeatedly during Quaternary sea-level variations, and the proportion of TWWHA karsts affected is small, albeit rising waters could destroy some soft-sediment cave content, resulting in some loss of stratigraphic, palaeo-environmental and cultural information in caves close to present sea-level, for example on the Lower Gordon River).

Low	**Priority Level**	**Low**
	Criteria	No immediate decisions required, but low risks should be maintained under review. It is expected that no new actions will be required unless these risks become more severe.
	Potential Impacts	**Rationale for priority level**
	Degradation of alkaline pans: Some drying and deflation of alkaline pans on carbonate rock valley-bottoms during projected drier summer conditions is possible (Section 4.2.6), albeit generally poor drainage means such impacts have lower likelihood of occurring.	Unlikely, minor consequences for geodiversity (if such changes occur, impacts on dependant vegetation likely to be greater than impacts on geomorphic or soil processes *per se*).
	Degradation (mainly erosion) of relict hard - rock geoheritage (landform morphologies and bedrock contents, e.g., fossils, minerals, structures, stratigraphy, etc): Some degradation of a wide range of relict hard-rock geoheritage features may occur in response to changing fluvial, mass movement, coastal and other erosion processes, however most changes are likely to be slow and generally negligible by 2100 (Sections 4.3.4, 4.3.5). Small scale hard rock surface features (e.g., karren) or bedrock contents of limited extent (e.g., restricted fossil or mineral occurrences) are likely to most susceptible but changes will probably only be noticeable in a few circumstances (e.g., some types of rocky coasts susceptible to sea-level rise). Little noticeable change to large scale bedrock features is expected, and indeed a long term reduction in alpine periglacial processes may result in reduced rates of erosion of hard rock relict glacial and periglacial landforms in alpine areas (Section 4.3.4).	Rare, some minor instances of degradation might occur (hard rock elements of geodiversity are likely to be generally the most resilient to climate change impacts).

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