Government of **Western Australia**
Department of **Environment and Conservation**

INTERIM RECOVERY PLAN NO. 325

Stromatolite community of stratified hypersaline coastal lake - Lake Thetis

2012- 2017

May 2012

Department of Environment and Conservation

FOREWORD

Interim Recovery Plans (IRPs) are developed within the framework laid down in Department of Environment and Conservation (DEC) Policy Statements No.'s 44 and 50.

IRPs outline the recovery actions that are required to urgently address those threatening processes most affecting the ongoing survival of threatened taxa or ecological communities, and begin the recovery process.

DEC is committed to ensuring that threatened ecological communities are conserved through the preparation and implementation of Recovery Plans or Interim Recovery Plans and by ensuring that conservation action commences as soon as possible and always within one year of endorsement of that rank by DEC's Director of Nature Conservation.

This Interim Recovery Plan will operate from 2012 but will remain in force until withdrawn or replaced. It is intended that, if the ecological community outlined in this plan is still ranked Vulnerable, that this IRP will be reviewed after five years and the need for a full Recovery Plan will be assessed.

This IRP was given Regional approval on 11 June 2012 and was approved by the Director of Nature Conservation 25 June 2012. The allocation of staff time and provision of funds identified in this Interim Recovery Plan is dependent on budgetary and other constraints affecting DEC, as well as the need to address other priorities.

Information in this IRP was accurate at May 2012.

ACKNOWLEDGMENTS

This Interim Recovery Plan was prepared by Nick Casson, Valerie English and Wendy Chow.

The following people provided valuable advice and assistance in the preparation of this Interim Recovery Plan:

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CITATION

This Interim Recovery Plan should be cited as:

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SUMMARY

Name: Stromatolite community of stratified hypersaline coastal lake - Lake Thetis

Description: Lake Thetis contains a distinctive and diverse group of benthic microbial assemblages, each producing a mat that is associated with one specific zone within the lake. Crenulate cyanobacterial mats occur in the low-lying areas adjacent to the lake. Lithified stromatolites, resembling those at Shark Bay, with patches of living cyanobacterial mats and nodular mats characterize the littoral areas. Filamentous mats reside in cavities and coat the surface of the flocculant mat in the basin, a mobile diatomaceous mat occurs in the shallows, and thick flocculant mats of phototrophic prokaryotes, other microbes and/or diatoms occur in the central basin.

Lake Thetis differs from other coastal saline lakes because it has benthic microbial mats adjacent to the lithified stromatolites and well-developed flocculant mats in the basin. Under current conditions ‘microbial reef-forming’ communities and flocculant mat communities are both scarce, and such strong joint development is unusual. Also, some stromatolites have branching columns which are rare in modern environments.

DEC Region: Midwest

DEC District: Moora

Local Government: Shire of Dandaragan

IBRA Region: Swan Coastal Plain

Current status: The microbialite community was endorsed as vulnerable on the list of threatened ecological communities in Western Australia by the Western Australian Minister for the Environment in November 2001.

Habitat requirements: The typically alkaline and nutrient-poor water of Lake Thetis gives rise to waters that are ideal for the growth of microbial mats and stromatolitic microbialites. The *Calothrix* and *Scytonema* spp. which dominate the crenulate mats rely on a layer of organic-rich sediment just a few millimetres thick. Most of the microbial mats require sufficient sunlight for growth and survival except for the filamentous mats that can survive in the deeper parts of the lake and experience reduced light penetration (Grey *et al.* 1990).

Habitat critical to survival, and important occurrences: The habitat critical to the survival of the microbialite assemblage is the area of occupancy of the known occurrence, and the local catchments for the surface waters and for the regional groundwater on which the community may depend. The extent to which chemicals can effectively travel through groundwater and the limestone to the lake and potentially contaminate it are also important considerations. Lake Thetis contains the only known example that contains a form of branching microbialite in close association with a well-developed flocculant mat and other mats, so this occurrence is critical to the survival of the community.

Objective: To maintain or improve the overall condition of this microbial community and reduce the level of threat.

Guide for decision-makers: Any on-ground works (including clearing, new firebreaks, proposals to spray herbicides, construction or industry, with potential to cause changes to water levels or quality) in the immediate vicinity of the Lake Thetis microbialite community will require assessment and regulation. Proponents should demonstrate that on-ground works will not have an impact on the community, or on its habitat or potential habitat.

Criteria for success:

- An appropriate buffer zone and water quality thresholds that protect the hydrological processes that sustain the microbial community of Lake Thetis are determined and maintained.
- Maintenance of the key self-sustaining structure-forming microbial taxa in Lake Thetis (stipulated in Appendix 1 for the domes, water body, and flocculent mat). This will be measured as retention of particular taxa and a stable spectrum of other microbial taxa in the known occurrence over the life of this plan.
- Identification of existing and potential threatening processes affecting the microbial community and habitat in Lake Thetis habitat.

Criterion for failure:

- Loss of key self-sustaining structure-forming microbial taxa in Lake Thetis.

Summary of Recovery Actions:

• Coordinate recovery actions	• Monitor and manage water quality and hydrology
• Map critical habitat	• Monitor and manage water levels
• Clarify and monitor composition, extent and health	• Liaise with stakeholders to manage water quality
• Conduct research to clarify biological threats: ameliorate threats	• Monitor and protect suitable native vegetation buffer

• Protect from physical damage	• Manage fire regimes and weeds in buffer
• Manage scientific access	• Report on success of management; incorporate results into future management
• Continue monitoring physical condition and composition of lake and stromatolites	

1.0 BACKGROUND

1.1 History, defining characteristics of ecological community, conservation significance and status

Three basic types of contemporary microbial structures, or ‘microbialites’, which are formed in benthic areas are stromatolites, thrombolites, and structures that have a less tangible internal framework. Stromatolites have a layered internal structure, thrombolites have a clotted internal appearance and others such as algal mats and tufa have an ill-defined structure. Fossil records mainly contain stromatolites, some thrombolites, and very few leiolites (stuctureless forms) or dendrolites (the branching forms; see Grey and Planavsky 2009). Microbialites occur in marine, fresh or hypersaline waters, and from sub-tropical to cool temperate environments (Moore 1993).

Fossilised stromatolites are amongst the earliest recorded forms of life on earth. They dominated the Pre-Cambrian period, between 3.5 billion and 600 million years ago. Around 570 million years ago (early in the Phanerozoic era) these formations declined, possibly due to the evolution of grazing and burrowing animals that disturbed the structures. The stromatolites then became more dominant as they probably became more resistant to grazing and burrowing animals. Subsequently an increase in the availability of free oxygen led to the evolution of faster-growing marine organisms such as corals and macroalgae, which then resulted in the decline of the stromatolites as a result of spatial competition (Moore 1991; Grey and Planavsky 2009). Microbialites have great scientific importance, for although they are substantially different from their ancient relatives they provide some insights into some of the oldest forms of life on earth and into historical environments through information encrypted within their structure. Worldwide, these structures are restricted to a few areas of limited extent including the Bahamas, Mexico, Bermuda and Western Australia (Moore *et al*. 1984). Living marine stromatolites are known from few localities in the world.

Lake Thetis is a permanent, hyper-saline lake located on the coastal plain 1.25km inland from the Indian Ocean and less than 1km due east of the coastal township of Cervantes. Lake Thetis occupies a deflation basin with limestone pavement situated between Holocene parabolic and nested parabolic dunes, and is separated from the ocean by a relict fore-dune plain (Gozzard 1985). This relict is better known as a beach ridge plain which has developed as sea-borne sands have built up to a cuspate foreland. At Cervantes they develop due to the conjunction of geological stability, low coastal relief, massive sand deposits, fringing reefs, and the climatic setting (V & C Semeniuk Research Group 2004; Shepherd and Eliot 1995).

The lake is isolated from major surface drainage systems and is fed by surface flow and may be fed by the flow of groundwater. Inflows are rich in calcium and carbonates (McNamara 2001; Kerns 1997). The lake waters are typically alkaline and nutrient-poor which means they are ideal for the growth of benthic microbial communities (Grey *et al*. 1990).

Microbial communities incorporate grains of sediment at a very slow rate and build structures that on average are about 2000 years old when they reach a height of one metre. The Lake Thetis stromatolites have been dated as about 1100 ± 250 years old, while the organic matter rich basin sediment at 70cm is 3370 ± 260 years old (Grey *et al* 1990). A special characteristic of some of the Lake Thetis stromatolites is that they have internal columnar structures which are considered to be a modern rarity. Such branching, which results in a complex-ramified structure, shadows the dendrolites found in the Cambrian fossil record (Monty 1973; Grey and Panavsky 2009). Branching columns have been recorded from some recent lakes but none of these examples resemble the narrow, closely-spaced and almost parallel columns from Lake Thetis (Grey *et al.* 1990).

The concentration and/or ratio of constituents in the brine is unique in each coastal, calcareous, saline/hypersaline lake and embayment in Western Australia. Each has a different development history caused by varying degrees of fluctuation, mixing, and marine, terrestrial and atmospheric inputs and outputs (Arp *et al*. 2001; Grey *et al.* 1990; Burke & Knott 1989; O’Leary 2007). These issues have helped to determine the resident calcifying biota and the nature of the structures formed. For instance macrophytes, such as charophytes, are only present at some lakes (Grey *et al*. 1990; Burke and Knott 1989), while microbial communities show considerable diversity between structures and in response to brine concentration (Grey *et al*. 1990; Goh *et al*. 2009). The brine and the pools of chemical constituents interact with the resident microbial biota at various scales. It is evident that at Lake Thetis the close relationships of cyanobacteria and sulfur bacteria underpins the microbial dynamics in the massive sediment at the macro-scale and the formation of domes at the micro-scale (Grey *et al*. 1990; Grey and Panavsky 2009). This pivotal role has interplay with the other elements in the communities, chiefly species in the domain Bacteria and the domain Archaea (refer glossary), which in turn also feeds into regulatory and structural functions (Goh *et al*. 2009).

Table 1: Extent and location of occurrence

Occurrence Number	Description of Location	Approx area (ha)	Longitude GDA 94	Latitude GDA 94
1	Nambung National Park (R24522). 600m SE of intersection of Cervantes Road and Hansen Bay Road, Shire of Dandaragan.	~37 ha (in this section of the park; Lot 615 on Plan 43663)	115°4'52.522"	- 30°30'24.127"

1.2 Description of Occurrence

The stromatolites occur in the fringing shallows of Lake Thetis on land reserved for nature conservation and recreation. They are just one expression of the diverse microbial assemblage that occurs in the lake. The occurrence lies 1km east of the town of Cervantes in the Shire of Dandaragan.

Data on all known occurrences of threatened ecological communities are held in the threatened ecological community database at DEC's Species and Communities Branch, Kensington.

Biological and ecological characteristics

Lake Thetis is characterised by a diverse assemblage of benthic microbial communities, each producing a distinctive mat type confined to specific zones, and in some cases associated with lithified stromatolites. Distribution of mat communities is determined by environmental controls, a factor clearly demonstrated by the development of microbial zones that reflect seasonal and longer term variations in lake levels (Grey *et al.* 1990; Grey & Plavansky 2009). The Lake Thetis stromatolites and mats differ from other Western Australian occurrences such as Hamelin Pool and Lake Clifton in gross morphology, such as internal branching, and in the spectrum of benthic microbial communities that have been identified.

Lake Thetis is comprised of a series of concentric zones, each dominated by a different microbial mat type. These are crenulate, nodular, filamentous, diatomaceous and flocculent mats.

Crenulate mats grow in seasonally flooded high foreshore areas around Lake Thetis. These mats consists of a few millimetres of organic-rich sediment intercalated with lake sediments comprising mainly calcareous mud, and is underlain by coarse calcareous sand. The mat contains the filamentous cyanobacteria identified as *Calothrix* and *Scytonema* as well as small colonies of the coccoid cyanobacterium, *Gloeocapsa*. Traces of this benthic microbial community are rarely found in the underlying sediment.

A well developed nodular mat is restricted to the splash zones around the sides of stromatolite domes in the calm waters along the south-western shoreline of Lake Thetis. The nodular mat consists of coccoid cyanobacteria, principally *Gloeocapsa*, with variable quantities of diatoms depending on seasonal lake level. These organisms secrete mucilage which, along with the layer of living mat, forms a thin coating on the lithified nodules. Copious mucilage production provides a matrix for sediment accumulation and carbonate precipitation.

The domes are just one of the diverse forms of microbial mat communities in the lake, however, they draw attention because they form the most obvious structures at the lake. They are marked by a thin outer rind that is dominated by coccoid cyanobacteria (*Gloeocapsa* and also *Entophysalis* (Arp *et al*. 2001)) and deeper layers that are dominated by filamentous cyanobacteria (*Scytonema*) and by branching and tufts. The significance of such a split in the structure has not been determined. It may be functional or it may mark a key change that occurred in the environment in the relatively recent past (Reitner *et al*. 1996). Cavities in the older sub-fossil portions of the microbiolites can contain *Scytonema* and *Oscillatoria* (Grey and Planavsky 2009).

Filamentous mats occur in two locations. Firstly, in areas of reduced light penetration, as well as within cracks of lithified plates and angular fragments on the lower marginal shelf. This mat mainly consists of oscillatorian cyanobacteria including chasmoliths (see glossary). Secondly, a similar filamentous mat occurs in the deeper parts of the lake where it forms a thin, fragile, often incomplete film comprising the uppermost layer of flocculent mat.

The diatomaceous mat forms an orange-brown gelatinous band in the shallows, usually just below or sometimes coating the nodular mat. Diatom frustules (see glossary) are a significant component of the lithified surface of many of the Lake Thetis stromatolites. Microscopic examination of fresh samples of the benthic microbial community forming the gelatinous band indicates that diatoms as well as cyanobacteria are consistently associated with carbonate particles and may have a role in trapping or precipitating carbonate sediments (Grey 1990).

The floating flocculant mat comprises a relatively thin (1-2mm) surface mosaic of brown-to-blue-green patches over a massive pinkish-red accumulation of biogenic sediment. This community colonises the bottom of the central, submerged basin, of Lake Thetis. The upper film is made up of several species of oscillatoriacean cyanobacteria and other non-phototrophic filamentous bacteria such as *Beggiatoa* sp., a boundary species that tolerates oxygen and oxidises hydrogen sulphide (H_2S). Other major contributors to biomass in this community include several pennate (long tapering) and naviculoid (boat shaped) diatom species and a small unicellular, coccoid cyanobacterium (*Synechocystis*). The underlying bulk of the 'mat' lacks oxygen and has red–purple organic material mainly comprising purple sulfur bacteria (anoxygenic, H_2S utilizing photosynthetic bacteria, Thiocystis/Thiocapsa group). This grades into the sediment of carbonate mud and shell fragments (Grey *et al*. 1990). The massive sediment in the lake basin is also likely home to a range of bacteria including sulphur-reducing bacteria and other chemautotrophs.

Purple tides typical of such species have been observed at the lake (Bauld *et al*. 1986; Grey *et al*. 1990). These bacteria play an integral role in adjusting the alkalinity of the brine at the macro and micro scales, that is in the lake water and within microbial structures (Burns *et al*. 2008; Goh *et al*. 2009).

The water column has been largely overlooked, but is likely to contain blue-green bacteria, diatoms, other bacteria, and perhaps very low levels of archaea. Macroalgae do not appear to be present. The archaea remain unsampled at Lake Thetis despite making up much of the other benthic microbial systems, including the inner communities of stromatolites (Goh *et al*. 2009).

There are at least three species of teleost fish in the lake. Two appear to be native and include a 'hardy head' ([1]D. Morgan pers. com.), and a slightly larger fish, probably a 'gobi'; these fish have been observed grazing the flocculant mat (Grey *et al.* 1990). Of concern is the apparent introduction of black bream which have a voracious appetite, and the provisional identification of Yellow-tailed Grunter and Gambusia in the lake (DEC and Department of Water field observations).

Invertebrates have not been studied, but it is clear that there are crustaceans, snails, nematodes and insects associated with the stromatolites (Grey *et al*. 1990).

At least 14 species of waterbird visit the lake and it is likely that they will affect nutrient inputs and outputs and could act as one means of microbial transmission from waterbody to waterbody (Birds Australia WA (Inc.) 26/02/2004; and www.birdata.com.au).

Hydrology

Lake Thetis is a small waterbody with maritime origins, which is fed by direct rainfall, surface water, and possibly by groundwater bearing calcium and carbonates. It loses water by evaporation. No rivers or creeks discharge into it. There is no evidence for active subterranean water exchange with the sea (Por 1985). The water level fluctuates around mean sea level simply because the lake sits close to sea level. The fluctuations actually follow seasonal trends closely related to rainfall, rather than the tides (Grey *et al.* 1990).

Salinity recordings can vary from 39-59 g L^{-1}. The ionic proportions of the lake water are idiosyncratic but reflect seawater origins (Grey *et al.* 1990; Arp *et al*. 2001; DEC records 2009, 2010).

The balance between rainfall, surface water flow, groundwater input and output (quantity and quality) and evaporation at Lake Thetis is unknown. The lake is apparently down-gradient in regional superficial flow. Other unknowns include the extent to which it would act as a preferred basin at this locality; the relative contributions of other sources such as deeper aquifers and seawater wedges, and wetlands to the east-south-east.

The Tamala and Lesueur limestone aquifers a few kilometres east of Lake Thetis have ground waters bearing only 1gm/L salinity (Kerns 1997). Similarly the water in the quarry ponds to the north is from 4 to 10 gm/L (Grey *et al*. 1990). The salinity of groundwater in closer proximity to the lake has not been investigated, apart from a shallow bore on the lake edge where it simply intercepted lake salinity.

The slightly elevated sulphate levels and an anoxic boundary dominated by sulphur bacteria may in part indicate concentration of incoming groundwater bearing H_2S and/or sulphate (SO_4).

The Department of Water (DoW) has installed a 7m and a 20m deep bores immediately west, to the immediate east, and to the north of Lake Thetis. Data from bores, data loggers and other sources are being analysed by DoW. Results will provide guidance for hydrological management, including helping to determine an appropriate buffer from developments that may impact hydrology. Near Lake Thetis the base of the Tamala limestone is about 30m below the surface and so the bores sample this and the overlying sand. About 2km east is a cluster of town water supply bores (bores 7/91, 1/85, 2/75 & 1/76), and from 5 to 20km east is a chain of DoW "Leeman Shallow" observation bores (bore numbers 1 to 4), which are still active (Kern 1997). The first two observation bores are ~80m deep and extend well

[1] Dave Morgan: Centre for Fish and Fisheries Research at Murdoch University

below the limestone into Lesueur Sandstone.

Paleohistory

The whole lake is a recent geological phenomenon, dating back about 5000 years to the mid Holocene (Hearty 2003; Telles *et al*. 2004). The water level has not remained stable, and the lake has been much larger than at present, and also smaller as indicated by former shores and terraces, but always with a collapsed sinkhole at its core (Grey *et al*. 1990; Grey and Plavansky 2009). It has experienced wetter phases and drier phases, marked by deposition and exposure and erosion of stromatolites respectively (Telles *et al*. 2004). The oldest stromatolite so far recorded is 1210 $\pm$ 260 years (Grey *et al*. 1990) which indicates that there may have been time for several waves of such structures to have developed in succession since Holocene times.

1.3 Historical and current threatening processes

In the past major threats included crushing by vehicles and uncontrolled pedestrian access, and high level disturbance to the buffering vegetation. This disturbance included mining and refuse dumping to the north that increased the risk of weed invasion, more frequent fire and input of sediment and ash. These disturbances have been significantly reduced recently.

Whilst the rock-like domes are persistent, it is not necessarily evident from visual cues to determine whether the structure-building communities are active, inactive, or deceased. This requires use of specialist techniques and knowledge to establish the status of the microbial community, and water monitoring to track component changes in the brine.

Present or potential threats to the microbial community in Lake Thetis arise mainly from hydrological, chemical and physical change as follows.

Nutrient enrichment and increases in other pollutants

Unallocated Crown Land (UCL) and land used for other purposes occurs within 50m of the lake edge to the east, 20m to the south, 190m to the north, and 240m to the west. This may not provide for an adequate buffer of vegetation to protect the hydrological processes required for maintenance of the microbial community in Lake Thetis. In addition, the town of Cervantes is now within 600 to 800m west of the lake, an oval and golf course occur about 650 to 900m north-west respectively, and a light industrial area occurs 350m north or approximately 200m with expansion. The Indian Ocean Drive (Pinnacles Road) and Hanson Bay Road are about 300m east and 350m west respectively. The town borefield is 1km to the east.

Cumulative changes to the brine in Lake Thetis may arise from nutrient enrichment, contaminants from a range of sources including residual leachates from old dumped garden waste or visitation, the use of any herbicides or pesticides, and leachates from a nearby industrial area or the town.

With increasing populations and subsequent rise in land use for agricultural practices, the concomitant rise in runoff of nutrients and other pollutants from properties that are up gradient may be a threat to the growth and survival of the stromatolites. Excessive irrigation and fertiliser application in the catchment, for example on agricultural land, private lawns and market gardens, has the potential to result in pollution of the lake due to leaching of contaminants to groundwater or through surface runoff. The first heavy rains in winter are known to flush large amounts of nutrients from urban and agricultural areas into wetlands (Davies and Lane 1996), and pesticides can also be mobile in water and sediment.

There are a number of sites around Lake Thetis where pollution may have already intercepted the shallow groundwater. These are a nearby disused limestone marl pit and garden refuse site, an adjacent light industrial area, and the car park servicing Lake Thetis.

There is a medium-high risk of groundwater contamination adversely affecting the stromatolite community. For stromatolites to continue to survive they need a specific combination of chemical balances within the water column and this may be disrupted if pollution enters the lake from nearby groundwater. There may also be outright toxic effects due to contaminants.

The most direct threat is likely to be herbicides used in the catchment or aquifer. If they reach the lake surface intact they may tend to concentrate around the domes as foam. Outright toxic effects of a common herbicide have been demonstrated on stromatolite microbes (Falcon *et al*. 2006).

Nutrients may also be concentrated at the domes by foams, however, this is similar to input from surface ash or organic detritus and from bird excreta, to which the communities are very likely to be adapted.

A sustained plume of dissolved nutrients could potentially affect the CO_2 system in the lake and the calcium carbonate saturation, as phosphates and sulphates affect the total alkalinity. However such an input would need to be large and work in tandem with raised atmospheric CO_2, and other effects such as acid rain which is mainly a metropolitan issue.

Ultimately excess input of nutrients is likely to end up in the sediment, which clearly has a role as an organic matter and nutrient sink which is another way it buffers the system.

Physical crushing and active recreation

There has been a level of historic crushing due to pedestrian access, and four-wheel drive activity. The latter was estimated to have destroyed about 25% of the stromatolite community (Gillen 2007).

General impacts are likely to increase as the population of the area increases, metropolitan access improves, and tourist visitation increases, such as a consequence of the construction of the Indian Ocean Drive. Other activities such as canoeing and fishing, and even dog-walking, would also have significant impact on the stromatolites through crushing, abrasion, and contamination. Although this will be moderated by the buffering vegetation, the lake sediment, and even the limestone, it still will result in an additional sustained input to a low nutrient catchment. This was generally addressed by the following work in 2008/2009:

- installation of signs to indicate the significance of the stromatolites;
- a loop-walk and boardwalk, bird hides, a lookout, and a day-use area with parking and picnic facilities;
- a boardwalk, track closure and revegetation as barriers.

Other possible supplementary measures could include other means of encouraging visitors to remain on the pathway and boardwalk.

Introduced fauna (fish)

The Lake appears to have 2 to 3 species of small native fish, and several invertebrate species (DEC observations; Grey *et al*. 1990); to 2010. Invertebrates are not obvious inhabitants of the stromatolites as they are at Lake Clifton (K. Grey pers. comm. 2010; Konishi *et al.* 2001).

Black bream are probably a modern introduction because they were not noticed until recently (Grey *et al*. (1990); [2]K. Grey pers. com.). This species was introduced to Lake Indoon to the north-east and other lakes (B. Morgan pers. comm.). Besides the bream there are also tentative identifications of Gambusia ([3]S. Buitenhuis pers. comm.) and of Yellowtail Grunter ([4]M. Hammond pers. comm.).

All introductions have the potential to directly and indirectly alter the ecosystem dynamics and may consume microbial communities, invertebrates, and indigenous fish, and so also alter fish diversity and/or abundance, and nutrient pools and cycling rates. Polychaetes and molluscs form a high proportion of the bream's diet in Lake Clifton (Sarre *et al*. 2000), as do invertebrates at Lake Indoon (Smith 2007). If they graze the sediment and the flocculant mat covering it they can affect the oxic/anoxic boundary (the sulphur reducing/ sulphate oxidising interface) and the buffering of the lake and regulation of the system. The latter is likely because sediment often forms a high proportion of their diet (Chuwen *et al.* 2007). Consequently their foraging may also directly degrade the stromatolites. Such foraging is greater at higher salinities (Partridge and Jenkins 2002).

Current data from Lake Thetis indicate that the water quality may at times be unfavourable for black bream but have not been found to be enough to exclude them outright as yet.

Erosion and sedimentation

Vehicles had visited Lake Thetis for many years and had contributed to the compaction of soils which prevented peripheral vegetation from growing (Gillen 2007). The removal of this vegetation may have let more nutrients enter the lake because of a partial reduction in filtering by fringing vegetation. Increased sedimentation, including from construction activities adjacent to the lake can physically affect microbes via burial and/or blocking light penetration and hence photosynthesis.

Alterations to surrounding vegetation

As part of the restoration work of 2008/2009 vegetation around the lake was rehabilitated as a buffer and filter to water-borne contaminants such as nutrients, and to remediate spoil and control weeds. A vegetated buffer of at least 200m from the high water mark is required in sandy soils to prevent nutrient enrichment in wetlands (Davies and Lane 1996). The program included a survey of the vegetation bordering the lake, in particular adjacent to the stromatolites

[2] Kath Grey: Geological Survey of Western Australia, Department of Mines and Petroleum
[3] Steven Buitenhuis: DEC Moora
[4] Mike Hammond: Department of Fisheries, Western Australia

and selective spraying of grassy weeds in the quarry and other disturbed areas with glyphosate-based spray. The risk of fire would have been reduced by removal of grassy weeds in the understorey, as they are likely to be more flammable than the original native species and this in turn reduces risk of short term flush of nutrients being washed into the lake from fire and from the loss of the peripheral vegetation as a filter for excessive nutrients entering the lake. Chemicals used for weed control may, however, impact on the stromatolites if used immediately adjacent to the structures.

Declining water levels

The contemporary issues are primarily declining rainfall and, if the lake is groundwater dependent, groundwater abstraction (see Yesertner 2008).

During wetter phases the stromatolites are sustained as they have sufficient water to cover the active surface of the structures while still having adequate levels of light, nutrients, gases, and structure-building chemicals such as calcium and carbonate ions. The water level at Lake Thetis currently fluctuates seasonally by up to 0.5m (Grey *et al.* 1990). It rises in winter through direct rainfall and possibly increased groundwater input, and declines over summer by evaporation, exposing the stromatolite domes to varying degrees. The groundwater levels may vary yearly with climatic conditions and land uses (Lindsay 2002). However, if the lake partly depends on groundwater input, and if groundwater abstraction in the catchment acts to reduce such input, a falling water level may expose the stromatolites and other microbial communities and retard their development.

Declining water levels may therefore have the potential to threaten the current phase of stromatolite deposition, particularly if water influx to the lake declines due to factors other than natural fluctuation within normal ranges, and if the lake permanently shrinks due to declining rainfall and/or abstraction. If it shrinks the 1200 year old stromatolites could become exposed and the deposition could be replaced with erosion. Such changes may interfere with stromatolite development for a period but are unlikely to halt it over the longer term. The sedimentary evidence suggests that despite periods when the stromatolites were exposed and actively eroding, the microbial communities still persisted and ultimately regenerated these structures. It also appears that there may have been several waves of stromatolites because the shoreline has moved a great deal and the estimated age of the contemporary domes is less than the age of the lake.

If such changes are cyclical and relatively rapid and short term the microbial community probably has the capacity to accommodate them. The worst case scenario would be drying out of the lake and the sediment, with inherent risk to the biogeochemistry of the sediment such as loss of the anoxic interface and acid-sulphate development. Metals have not, however, been tested in the lake, although iron that would be required for acid sulphate release is not believed to be a major component of the lake sediments (Grey *et al*. 1990).

Changes to the salinity of the brine

There is a moderate threat to the existing cohort of microbialites and other microbial communities from rapid and/or sustained change to the salinity of the brine. Absolute salinity is basically the sum of the main ions in solution. Under likely drying/concentrating conditions the main threat is loss of microbes with moderate salinity tolerances from the community and so alteration to the community composition and dynamics including structural processes. Alternatively, dilution of the lake is unlikely because the resident chemicals would simply re-dissolve if freshwater inflow increased.

There is only a short-term record of the salinity range, which from 1985 to 2010 has been from 39 to 59 g/L (field conductivity and absolute salinity values; Grey *et al*. 1990; DEC records 2009, 2010). The long-term fluctuations will only emerge with prolonged monitoring across the lake. This is linked to also establishing the quality, quantity and rate of inputs and outputs of water to the lake and the interaction with issues such as such as declining rainfall and, if the lake is groundwater dependent, groundwater abstraction. The following studies would be required to understand the lake hydrology:

- lake level
- lake salinity and other parameters and typical fluctuations, and the presence of gradients and the degree of mixing or stratification
- relative terrestrial groundwater input (and/or output)
- any subterranean marine input
- output due to evaporation and,
- input due to direct rainfall and surface runoff.

In addition to capacity to tolerate water-level fluctuation over the long term, the microbial community probably has the capacity to tolerate fluctuations in salinity. This is because the lake volume and therefore dilution has clearly varied greatly over time (Grey *et al*.1990; Grey and Plavansky 2009; Telles *et al*. 2004). It is also evident that a strain of the purple sulphur bacteria similar to that in the lake has adapted to hypersaline conditions (Bauld *et al*. 1986). This is the case for other likely resident microbes including the archaea, several of which are halophilic. Resting spores can allow microbes to survive through adverse conditions, and these appear to exist at Shark Bay (Goh *et al.* 2009).

The impact of changes in salinity and other water quality parameters on the stromatolites may be dependent on the level of stratification and mixing of inputs such as groundwater and lake water. Lake Thetis does not appear to experience a strong level of stratification within the water column, though this has not been closely studied. Relatively low salinity (when compared to hypersaline lakes such as the Rottnest Island salt lakes), shallow depth and the high wind and wave action promote a reasonably even spread of total dissolved solids (TDS).

Constant wave action, which promotes mixing, may have caused some stromatolites and microbial mats to develop poorly on certain areas of Lake Thetis, as the brine appears to concentrate in select unmixed mini-lagoons over summer (Reitner *et al*. 1996). Nonetheless, some species from the nodular mat community still persist in tiny cracks and hollows which suggests that high wave activity affects mat accumulation (Grey *et al.* 1990).

Other changes to the brine

Brine constituents help to determine the macro-ecology and help favour microbialites. The brine is also important for its buffering ability including alkalinity and the CO_2 system. The threat of changes to brine constituents from factors such as declining water inputs and extraneous chemicals is moderate.

A range of other factors may affect the brine. These include a change in the brine composition arising due to a change in relative contributions from all sources, or a change in the nature of incoming sources. Elevated carbon dioxide effects such as raised acidity/initial lowering of pH as CO_2 dissolves, or raised dissolved inorganic carbon as the dissolved CO_2 dissociates. Specifically the nature of the brine may alter due to change in the speciation of the things contributing to alkalinity such as carbonate, bicarbonate, borate, phosphate, but not the total alkalinity, which is always conserved (Pankow 1991). A potential, very long-term, risk is that the pH may move from its current bicarbonate equivalence point in the carbonate-bicarbonate series, with major consequences for structural deposition.

Different threats arise if the lake is dried out or diluted. Under likely drying/concentrating conditions the concentration of calcium carbonate will simply remain above the threshold that the cyanobacteria prefer and will rise in step with the Mg/Ca ratio until they precipitate or are left as an evaporite. The microbial community already tolerates a 2 to 3 fold annual jump in saturation in some places (Reitner *et al*. 1996). The salinity may also rise.

The main threat under drying conditions would be the ultimate exposure of the lakebed, with the collapse of the buffering input of the sediment, and the potential for the development of acid sulphate soils. Rewatering a drying lake would be problematic as matching current water quality and screening out foreign biota would be difficult.

An understanding of these processes would require monitoring of ‘total’ alkalinity, salinity, pH and other CO_2 system parameters.

Fragmentation in the hinterland

It is important to keep the brine within the range of its naturally oscillating levels in response to rainfall, surface water inflow, and evaporation, and any natural groundwater input. The uncleared land to the east of the lake is a partial means of protecting the lake from neighbouring contamination, and other activities that may impact water quality and levels.

The catchment for all of these functions is not just the inter-dune swale in which the lake sits, but also any regional groundwater which may make input to the lake.

1.4 Benefits to other species/ecological communities

The land that surrounds the microbialite community contains a Priority 2 floral taxon, *Acacia lasiocarpa* var. *lasiocarpa*, which may benefit from the recovery actions proposed to manage and rehabilitate the buffer vegetation.

1.5 International obligations

This plan is fully consistent with the aims and recommendations of the Convention on Biological Diversity, ratified by Australia in June 1993, and will assist in implementing Australia’s responsibilities under that convention. The ecological community covered by this plan is not specifically mentioned in international agreement, so the plan will not otherwise affect Australia’s international obligations under any particular agreement.

1.6 Role and interests of indigenous people

A search of the Department of Indigenous Affairs Aboriginal Heritage Sites Register, and enquiries with the South West Aboriginal Land and Sea Council, has identified that there are no sites of Aboriginal significance within or in close proximity to the TEC covered by this plan. Indigenous involvement in the implementation of recovery actions will be encouraged, and this is discussed in recovery actions.

The South West Aboriginal Land and Sea Council (SWALSC), an umbrella group, covers the areas considered in this plan. Comment was sought from the Council about any aspects of the plan, but particularly about the proposed on-ground actions. No areas of the ecological community were identified as containing sites known to have particular aboriginal significance. No general significance to indigenous people has been identified for the ecological community. Action 1 identifies the intention to continue liaison with relevant indigenous groups.

1.7 Social and economic impacts and benefits

There is potential for social and economic impacts of conservation and protection at two levels, the immediate locality and the wider catchment.

The lake occurs in the Nambung National Park and has been managed by the Department of Environment and Conservation (DEC) as an adjunct to the national park since 2005. Control of pedestrian access by means of the board walk and walk trails has potential to allow the aesthetic values of the community to be appreciated without degrading the community, and this provides a social benefit. Where specific active recreational pursuits such as driving around the lake edge are prevented through access control, this may be perceived as a social impact, however such access control also helps to prevent the continued degradation of the community and to maintain other social benefits.

The town of Cervantes is now within 600 to 800m west of the lake, an oval and golf course occur about 650 to 900m north-west respectively, and a light industrial area occurs 350m north or 200m with expansion (Grey and Planavsky 2009; distances approximate). In addition, the Indian Ocean Drive and Hanson Bay Road are about 300m east and 350m west respectively. The town borefield is also 1km to the east (Water and Rivers Commission 1999). The extent to which such inputs and abstraction from groundwater affect the lake is yet to be determined.

Much of the wider catchment for the borefield is covered by Nambung National Park and the southern Beekeepers Nature Reserve, both of which are vested in the Conservation Commission. The remaining part of the recharge area is private land that is used for sheep grazing and other extensive agricultural activities.

The lake habitat may be threatened by proposals where hydrological change may result from developments on adjacent land. Implementation of actions such as seeking to protect the hydrological processes in the adjacent community may result in an impact on adjacent development.

Wetlands such as Lake Thetis that contains this community provide various ecosystem services such as absorption of nutrients and other chemicals from polluted surface and groundwater. These services would have an economic value which is lost when wetlands are cleared and filled.

1.8 Affected Interests

This microbial community is located within the Shire of Dandaragan on reserved land managed by DEC. It is also used for local recreation, and visited by tourists. Surrounding lands are managed by other authorities including the Shire of Dandaragan and private landowners that may be affected by the implementation of this plan if developments are proposed for these lands.

1.9 Evaluation of the Plan's Performance

DEC, in conjunction with the recovery team, will evaluate the performance of this plan. The plan is to be reviewed within five years of its implementation. Any changes to management or recovery actions will be documented accordingly.

1.10 Guide For Decision-Makers

Section 1.6 above provides details of current and possible future threats. The lake system is likely to require significant buffers to protect the water levels and quality. Proposed developments that may have significant impact on the surface or ground-waters, leading to either changes in water quality or levels in the lake, require assessment and regulation. Proponents should demonstrate that on-ground works will not have an impact on the community, or on its habitat or potential habitat.

1.11 Conservation status

The stromatolite community of coastal brackish lakes is ranked as a Vulnerable ecological community under criterion B) as follows:

- The ecological community may already be modified and would be vulnerable to threatening processes, is restricted in area and/or range and/or is only found at a few locations.

1.12 Strategies for recovery

- To influence the management of Lake Thetis and the land management within the surrounding area, so maintaining natural biological and non-biological attributes and processes of the site that underpin the natural processes in the community.

- To conduct appropriate ecological research on the community to develop further understanding about the management actions required to maintain or improve its condition.

2.0 RECOVERY OBJECTIVE AND CRITERIA

2.1 Objective

To maintain or improve the overall condition of this community in the known location and reduce the level of threat.

2.2 Criteria for success:

- An appropriate buffer zone and water quality thresholds that protect the hydrological processes that sustain the microbial community of Lake Thetis are determined and maintained.
- Maintenance of the key self-sustaining structure-forming microbial taxa in Lake Thetis (stipulated in Appendix 1 for the domes, water body, and flocculent mat). This will be measured as retention of particular taxa and a stable spectrum of other microbial taxa in the known occurrence over the life of this plan.
- Identification of existing and potential threatening processes affecting the microbial community and habitat in Lake Thetis habitat.

Criterion for failure:

- Loss of key self-sustaining structure-forming microbial taxa in Lake Thetis.

3.0 RECOVERY ACTIONS

Completed actions

The former shire reserve that included the lake was incorporated into Nambung National Park in 2005.

Current lake boundaries have been databased and mapped by DEC.

Grey *et al.* (1990) completed a major study of the combined flocculent mat and massive organic matter rich sediment of the lake bed, the peripheral mats, which include the nodular mats and the microbialites, and the microbes of the water column.

A baseline survey of the domal structures was completed at the macro scale by DEC. They have been counted, geo-located and plotted.

DEC has established an informal consolidated 200m wide vegetated buffer measured from the high water mark to provide protection for the stromatolite community. Degraded areas on the northern side of the lake that provide a buffer for Lake Thetis have been rehabilitated. This included replanting through the impacted areas and selective weed control by physical and chemical means. General disturbance and infrastructure have been kept to a minimum within the buffer area, and planning processes are utilised to help implement this informal buffer.

DEC has restricted vehicle access to a proscribed area through the use of bollards, and interpretive signs, paths and a boardwalk established to help direct visitor access away from physical crushing of the mats and domes.

Water samples have been taken spasmodically from the lake since 1985. There has also been sampling from two bores in surface water and the saline fringe at the lake (Grey *et al*. 1990) and from the shallow aquifer to the east (Kerns 1997).

Department of Water installed bores to the west and north of the lake in 2010 to measure water levels and quality.

In 2011, 20 samples of microbial material were collected by DEC from a variety of the microbial assemblages and have been prepared and stored for DNA analysis of microbial composition. Water samples were also collected at the same time to link water and composition data.

Recommended Recovery Actions:

1 Coordinate recovery actions

The community's recovery is considered under the Moora District Threatened Flora and Communities Recovery Team. The Recovery Team will continue to coordinate recovery actions for the Lake Thetis stromatolite community. Input and involvement will also be sought from any indigenous groups that have an active interest in Lake Thetis. The Recovery Team will include information on progress in their annual reports to DEC's Corporate Executive and funding bodies.

Indigenous groups were contacted about actions included in this plan and will continue to be consulted about plan implementation.

Responsibility: DEC (Moora District)
Cost: $2,000 per year
Completion date: Ongoing

2 Map critical habitat

Current lake boundaries have been databased and mapped, however, the lake surface water catchment needs to be mapped. Department of Water commenced mapping the groundwater catchment in 2010.

While the central part of the lake has been stable for over 3000 years, it has fluctuated in size and is currently in a core-like contracted or 'drier' state. Aerial photography reveals previous shore lines of a lake that may have been some 4 to 6 times its current size (Grey and Plavansky 2009). This should be mapped as a long-term outer lake area to ensure an adequate buffer is maintained.

Responsibility: DEC (Moora District), Species and Communities Branch
Cost: $20,000 in the second year
Completion date: Year 2

3 Clarify and monitor the composition, extent and health status of the community

The 'health' or viability of the stromatolites has been established through a biological/petrographic study of the structures and this indicated that they were healthy at December 2000 and that the organisms that formed them were still dominant. The health of the stromatolites should continue to be monitored through compositional and structure studies.

A baseline survey of the domal structures has recently been completed at the macro-scale by DEC, and previously by Grey *et al.* (1990) Grey, K. and Plavansky, N.J. (2009). DEC counted the structures, geo-located and plotted them. This monitoring should be repeated at five year intervals, or at an appropriate frequency to coincide with detailed water monitoring. The possibility of monitoring numbers of intact stromatolites along a transect to determine gross changes, and the use of photographic monitoring to measure the extent of physical crushing should be investigated.

Scrub tests for the effect on sedimentation on the microbialite mat activity are also required due to recent indications of increased sediment deposition in the lake. This will involve 'scrubbing' the active microbial material off very small areas of the stromatolites, and leaving adjacent areas intact as 'controls', then quantitatively monitoring the deposition of microbial material and sediment, and sampling water quality at set time points. This will provide a quantitative measure of deposition of new sediment and of microbial growth.

Complementary macro-scale activities should include ongoing biennial inspection of the structures for the presence of constructive filamentous cyanobacteria. This requires good technical understanding of the variety of films and crusts, some of which are black (Grey *et al.* 1990). The actively forming microbialites, marked by the presence of an either filamentous or nodular calcifying mat, are found on the shallow, semi-submerged platform around the lake margin (Grey and Plavansky 2009).

The forms of mats described in Grey *et al.* (1990) require monitoring, i.e. crenulate mat, nodular mat, filamentous mat, diatomaceous mat, flocculent mat, and episodic purple tides that confirm the presence of sulphur bacteria. The status of the flocculent mat needs to be checked against previous observation by SCUBA, and the technique adapted if required. Collaboration with staff of the Geological Survey on a means of standardising methods will be required.

Visual checks for macroalgae and/or algal blooms should be conducted on a biennial basis (charophytes and other macro-algae, phytoplankton, including cyanobacteria).

The microbial diversity in Lake Thetis is still poorly known. Grey *et al* (1990) outlines the presence of the combined flocculent mat and massive organic matter rich sediment of the lake bed, the peripheral mats which include the nodular mats and the microbialites, and the microbes of the water column. This work does not indicate the full diversity of microbes, however, and therefore is not a good basis from which to determine change. Modern techniques such as genetic matching at intervals of 5-10 years will provide higher quality data. There are current studies utilising DNA techniques to indicate the range of microbial organisms present in different types of structures in the lake. The results of these studies will be available for use in future to underpin far more detailed monitoring of the composition of the lake's microbialites (see also Appendix 1).

Whether the distinct change in the dominant cyanobacteria in the domes corresponds to environmental changes, and the date of such change as indicated by the age of the layers above and below the change, also needs to be determined.

Responsibility: DEC (Moora District, Parks and Visitor Services, Species and Communities Branch)
Cost: $30,000 in Year 2, $2,000 pa thereafter
Completion date: Initial studies completed, monitoring ongoing

4 Conduct research to clarify biological threats; ameliorate threats

Introduced fish in Lake Thetis grazing on sediment probably threatens both the flocculent mat which regulates the system and the stromatolites. In order of concern of the introductions are black bream (*Acanthopagrus butcheri;* confirmed with large numbers of deaths in 2010), mosquito fish (*Gambusia* species; unconfirmed) and yellowtail grunter (*Amniataba caudavittata;* unconfirmed). The numbers of each fish species, but particularly black bream in the lake need to be monitored to help determine the potential level of threat from this source.

The highest priorities at present are to confirm that the bream are introductions and seek approval to control them. This will be through demonstrating that they can cause harm, to the satisfaction of the Department of Fisheries, then undertaking control measures such as selective netting. In addition, monitoring of water quality at low water levels/at the end of summer and/or drought will need to be continued to check if conditions are sufficient to kill the bream outright (salinity >65g/L and/or dissolved oxygen >1.00mg/L). The most reliable means of confirming the origin of the bream will be through RNA satellite work and comparison with other water body populations ([5]J. Chaplin pers. comm.). Lower priority work is to sponsor studies of the bream's diet, capacity to breed and persist, and age cohorts, provided this does not delay control measures.

An additional high priority action is to install signage at the lake indicating that introductions ('stocking') and fishing have unforeseen detrimental consequences to the ecology, and that they are prohibited and attract substantial fines.

To increase understanding about the indigenous species of fish and invertebrates present and their roles in the lake, the site should be sampled by the least disruptive means such as fixed nets (D. Morgan pers. comm.). Ideally fish should be sampled more than once each year to gain information about breeding status, recruitment events and population demographics/dynamics. The diet of the fish should also be examined, and the invertebrates should ideally be investigated to establish the fauna associated with the stromatolite matrix and biofilms present in the lake in general, and in the littoral /samphire area. The methods will need to be carefully selected to ensure minimal damage to the domes - for example, the north-west corner of the lake may be most suitable.

Responsibility: DEC (Moora District, Parks and Visitor Services, Species and Communities Branch) in consultation with Department of Fisheries
Cost: $5,000 for Year 1 (microscope), plus $5,000 per year for monitoring
Completion date: Ongoing

5 Protect the microbial community from physical damage

Vehicle access has been restricted to a proscribed area, and interpretive signs, paths and a boardwalk also help direct and moderate pedestrian activity and crushing of the mats and domes. Visitors do however leave the boardwalk to touch or walk on mats and domes. Other measures are therefore still required to regulate access, draw attention away from the domes, and/or seek co-operation from regular visitors. Increased presence of guides and/or rangers would probably assist in reducing damage.

An education program through the use of information boards and brochures that explain the importance of the site and features will continue to be developed and facilities upgraded as required.

Responsibility: DEC (Moora District, Parks and Visitor Services)
Cost: $20,000 for Year 2
Completion date: Ongoing

[5] Jenny Chaplin: Centre for Fish and Fisheries Research, Murdoch University

6 Manage scientific access to site

A register of identified sampling points is required for scientific access. The means of sampling needs to be very prescribed, with small samples, and interval between return samples kept to a minimum, especially with respect to stromatolite samples. This will require a dedicated departmental file or database and specific maps and photographs.

Responsibility: DEC (Moora District, Parks and Visitor Services)
Cost: $2,000 in Year 1 to develop protocol, $1,000 per year to manage system
Completion date: Ongoing

7 Monitor and manage water quality and hydrology

Water samples have been taken spasmodically from the lake since 1985, however, the parameters measured, the locations, timing, and the reporting of values has not been consistent. There has also been sampling from two bores in surface water and the saline fringe at the lake (Grey *et al*. 1990) and from the shallow aquifer to the east (Kerns 1997). DoW have also monitored lake water quality recently.

There is a need to undertake ongoing monitoring of the status of the lake waters and groundwater in a more consistent manner, when water levels are at maximum and minimum levels. Data should include water quality information including most common solutes, pH, salinity, 'total alkalinity', and temperature and water levels reflecting annual minima and maxima (see also Appendix 2), every three years. Monitoring will need to be completed in liaison with DoW, who are currently completing a three year sampling project.

Sampling should be from set points in the middle of the lake and edges adjacent to monitoring points for stromatolites so that water and biological monitoring are linked both spatially and temporally. Monitoring bores need to be installed to determine the quality and quantity of inputs and outputs, including the role of groundwater to the east and west, abstraction of the groundwater, and locations intended to intercept any potential contamination from the town centre to the north-west and industrial area to the north. Methods used should be consistent so that the data are comparable.

The water balance needs to be determined for the lake, in particular, if the lake is primarily dependent on rainfall, or if it is partly dependent on groundwater and/or seawater intrusion. DoW's analysis of recent bore and other data are expected to help clarify these issues.

DoW installed bores to the west and north of the lake in 2010 and will measure water levels and quality in the bores and the lake. Collaboration will be required with DoW on what is to be measured via bore placement and water quality assessment in the longer term. Future considerations for water monitoring should include:

- further long-term observation bore placement in east and west clusters, plus between the town and/or industrial area and lake, to ensure that preferred channels through the limestone, contaminant plumes, and the impacts of loss of more native vegetation in the lake buffer/hinterland are captured.
- water quality sampling parameters from the bores and lake.
- water table level measurement.
- establishing the extent of groundwater input and output, if any.
- if the production bores (located 3-4km east north east in the shallow aquifer) have impact on the hydrology
- relevant hydrological data being provided to DEC's TEC specialist group, especially lake analytes, water levels, and inputs and outputs.
- the annual period of inundation of the nodular mats and stromatolites needs to be consistently monitored and may require time-lapse camera, or observer.
- examining the relationship of the lakes to the east south east to Lake Thetis.

The baseline levels of nutrients, primarily phosphates, nitrates and sulphates in the lake and water sources including bores needs to be determined along with the origin and nature of any extraneous inputs.

Carbon dioxide (CO_2) raises acidity, and so affects the CO_2 system and calcium carbonate ($CaCO_3$) saturation which is a primary factor in brine chemistry and the ecology of the lake. The key concern is that it will cause flux in the main building material that underpins the stromatolites. For a brine like in Lake Thetis this could represent a significant pH change that may halt or retard stromatolite growth over a timeframe of 50 to 100 years. Changes in CO_2 will need to be tracked accurately through ensuring accurate and consistent pH, alkalinity and CO_2 readings (see Appendix 2).

Glyphosate formulation has been shown to be toxic to cyanobacteria, and foam may help concentrate such factors (Falcon *et al*. 2006). Glyphosate based herbicides pose a significant risk, in particular as they kill blue-green bacteria found in stromatolites and disrupt their DNA, and they are also nutrient enriching, namely through phosphates. Glyphosate chemicals should be completely avoided in areas that may flush into the lake through surface or groundwater, and this and other common and damaging contaminants should be tested in water samples wherever possible.

A key requirement for this plan is the determination of threshold levels of key water quality parameters that are required to sustain the microbialite community. Determining the extent of any groundwater inputs to the lake will also be very important for management decisions.

Responsibility: DEC (Moora District, Parks and Visitor Services, Species and Communities Branch)
Cost: $20,000 per year
Completion date: Ongoing

8 Monitor and manage water levels

The normal range of lake water levels is being determined through DoW's recent monitoring and requires analysis. The contemporary zone of nodular mat and stromatolite formation are clear, and the period of inundation or wave action can be determined (see Grey *et al*. 1990). The period of inundation of the stromatolites will continue to be monitored.

The likelihood of drying depends on the relative inputs from rainfall, groundwater and/or seawater intrusion, and the effects of total abstraction, which are yet to be determined. Currently much of the nodular mat and the domes are exposed to drying on an annual basis and the stromatolites may have tolerated regular recent brine concentration (Reitner *et al*. 1996).

Whether the lake had totally dried out during past dry phases is unclear, so whether the lake sediments could recover from such drying is unknown. Intermittent bands of calcium in the lake bed indicate that the lake has been very shallow, concentrated and supersaturated with calcium. Such layering may moderate any acidifying tendency in the sediment bed as a whole. In addition fine layers of oxide coated sediments indicate that the lake bed was exposed to the air at some time in the past, in which case it recovered (Telles *et al.* 2004).

It will be necessary to liaise with land and water managers to respond to results of water monitoring as appropriate, for example limiting groundwater abstraction rates if groundwater dependency is shown and the watertable falls or if saltwater intrusion occurs. This applies to both the surface and groundwater catchments.

Responsibility: DEC (Moora District, Parks and Visitor Services, Species and Communities Branch)
Cost: $5,000 per year
Completion date: Ongoing

9 Liaise with stakeholders to manage water quality within the lake

Information that should be provided to surrounding landholders to ensure actions on their lands do not impact the stromatolites should aim to minimise fertiliser use, avoid use of chemicals that may be toxic to the community and ensure other threatening processes are mitigated, such as the impacts of clearing and high stocking rates. A pamphlet that includes this information will be developed and provided to people who purchase land adjacent to the lake.

Communication with neighbouring land owners is required to ensure that fences adjacent to the stromatolites are maintained.

DEC will also liaise with agencies, such as the Shire of Dandaragan, Department of Water, and the Department of Agriculture and Food, to help ensure the management of land surrounding Lake Thetis does not adversely affect the stromatolite community.

Responsibility: Recovery Team; DEC (Moora District); liaison with other agencies
Cost: $3,000 per year
Completion date: Ongoing

10 Monitor and protect a suitable native vegetation buffer for the lake

The vegetated buffer adjacent to the lake serves to reduce cumulative impacts in the surface water catchment. A survey on the density, and the width of the vegetation buffer adjacent to the stromatolites as well as the lake boundary will be undertaken. Weeds may contribute to sediment movement and susceptibility to fire and should therefore be controlled in the vegetation adjacent to the lake, through means that are not damaging to the microbial community.

In the wider context there would be merit in maximising buffering of the lake if it is shown to be groundwater dependent, to protect the quality and quantity of water input and some of the wider catchment. Ideally this would include much of the recharge area to the east, but buffers of a few hundred metres on all sides would be an advantage. The Management Plan for Nambung National Park (Department of Conservation and Land Management 1998) recommends that the conservation values and existing use of the area of UCL to the east of the lake should be investigated to determine appropriate purpose and vesting.

Some of the wider catchment is covered by Nambung National Park and the Southern Beekeepers Nature Reserve, both of which are managed for the purpose of conservation. The remaining part of the recharge area is private land which is used for sheep grazing and other extensive agricultural activities. The town borefield is also up gradient of the lake in the regional groundwater to the east. As mentioned previously, results of current DoW monitoring will provide guidance for hydrological management, including helping to determine an appropriate buffer from developments that may impact hydrology.

It is important to preserve as much of the land-forming processes, including wind, drought and fire, as well as the actions of rainfall in the surface catchment, especially as they influence nearby surface soil development and movement and ongoing lake deposits. A logical reserve boundary could achieved by consolidating the area reserved for conservation east to include the strip of UCL about 200m wide to link to another section of Nambung National Park, and to also extend the reserve area south from the lake a suitable distance such as at least 200m as well.

There is risk from potential contamination and/or abstraction effects mainly to the east where regional flow originates and where major abstraction occurs. Reduction of cumulative impacts in the groundwater catchment if the lake is groundwater dependent may be best addressed through a regulatory instrument such as a joint agency Memorandum of Understanding or a policy that defines a special local and state government landuse/planning area, especially to the east of the lake.

Responsibility: Recovery Team; DEC (Moora District); adjacent developers in response to conditions placed on development
Cost: $10,000 for initial vegetation survey; $2,000 every year thereafter for flora monitoring and liaison
Completion date: Ongoing

11 Manage fire and weeds in buffer vegetation

Physical means of weed removal are preferred to chemical, and herbicides will need to be very carefully used in the vegetated buffer around the lake as common herbicides can travel with surface flow and are toxic to stromatolite cyanobacteria.

A fire management strategy will allow for the natural development of the adjacent plant communities that provide a buffer for the stromatolites. This will include an annual fire monitoring and reporting schedule. These issues are considered in a general sense in the Management Plan for Nambung National Park.

Maintenance of existing firebreaks is appropriate where they are already constructed, unless maintenance is likely to degrade the community or cause erosion. Recurrent maintenance increases the likelihood of weed invasion, and may introduce other soil biota or contaminants carried in on machinery. Conversion of hoed firebreaks to permanent surfaces should be considered. Where firebreaks are not deemed strategically necessary, they should be closed and allowed to rehabilitate.

The strategy for fire suppression procedures should be to minimise physical and chemical impacts on the stromatolites. Unregulated use of heavy machinery that disturbs vegetation and soil through the surface catchment is undesirable. The use of fire retardants in the surface catchment, and groundwater catchment, if groundwater dependency is indicated, may be of concern and means of control that do not incorporate foams need to be highlighted and promoted via planning, training, operation, and liaison between local DEC staff and FESA.

Responsibility: DEC (Moora District); in liaison with adjacent landholders, managers and FESA
Cost: $2,000 pa
Completion date: Ongoing

12 Report on success of management strategies; incorporate results into future management

Reporting will form part of annual reports prepared by the Recovery Teams for DEC's Corporate Executive, and will include results of analysis of monitoring results within an adaptive management framework. A final report will be presented as part of the next review and update of the recovery plan, if deemed necessary.

The requirements for appropriate management of a suitable vegetation buffer, monitoring of microbial composition, water levels and quality, weed and fire control, managing recreational and scientific access to the lake, and research to clarify threats will be incorporated into the Management Plan for Nambung National Park when it is revised.

If a recovery actions database is developed, information about recovery and monitoring for all TECs will be stored in that database.

Responsibility: DEC (Moora District; Species and Communities Branch)
Cost: $3,000 pa
Completion date: Year 5

Table 2: Summary of costs

Recovery Action	**Year 1**	**Year 2**	**Year 3**	**Year 4**	**Year 5**
Coordinate recovery actions	$2,000	$2,000	$2,000	$2,000	$2,000
Map critical habitat		$20,000			
Clarify and monitor composition, extent and health		$30,000	$2,000	$2,000	$2,000
Conduct research to clarify biological threats: ameliorate threats	$10,000	$5,000	$5,000	$5,000	$5,000
Protect from physical damage		$20,000			
Manage scientific access	$2,000	$1,000	$1,000	$1,000	$1,000
Continue monitoring physical condition and composition of lake and stromatolites	$10,000	$2,000	$2,000	$2,000	$2,000
Monitor and manage water quality and hydrology	$20,000	$20,000	$20,000	$20,000	$20,000
Monitor and manage water levels	$5,000	$5,000	$5,000	$5,000	$5,000
Liaise with stakeholders to manage water quality	$3,000	$3,000	$3,000	$3,000	$3,000
Monitor and protect suitable native vegetation buffer	$10,000	$2,000	$2,000	$2,000	$2,000
Manage fire and weeds in buffer	$2,000	$2,000	$2,000	$2,000	$2,000
Report on success of management; incorporate results into future management	$3,000	$3,000	$3,000	$3,000	$3,000

Summary of costs over five years:

Year 1 $47,000
Year 2 $95,000
Year 3 $27,000
Year 4 $27,000
Year 5 $27,000

Total **$223,000**

4 TERM OF PLAN

This Interim Recovery Plan will operate from June 2012 to May 2017 but will remain in force until withdrawn or replaced. After five years, the need to review this IRP or to replace it with a full Recovery Plan will be determined.

5 REFERENCES

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GLOSSARY

Bioherm: a carbonate rock formation, in the form of an ancient reef or hummock, consisting of the fossilized remains of corals, algae, molluscs, and other sedentary marine life, and commonly surrounded by rock of a different lithology.

Chasmoliths: living inside cracks in rocks.

Domain Bacteria: uni-cellular microorganisms that do not contain a nucleus and rarely harbor membrane-bound organelles. Although the term bacteria traditionally included all prokaryotes, the classification changed when it was noted that prokaryotes consist of two very different groups of organisms that evolved independently from an ancient common ancestor. These evolutionary domains are called Bacteria and Archaea.

Domain Archaea: uni-cellular microorganisms that are genetically distinct from bacteria and eukaryotes. They have no cell nucleus or any other membrane-bound organelles within their cells. Archaea possess genes and several metabolic pathways that are more closely related to those of eukaryotes, notably the enzymes involved in transcription and translation. Other aspects of archaean biochemistry are unique, such as their reliance on ether lipids in their cell membranes.

Frustules: The hard, siliceous bivalve shell of a diatom.

Oscillatory cyanobacteria*:* a genus of filamentous cyanobacterium which is named for its ability to oscillate. Filaments in the colonies can move against each other until the whole mass is reoriented to its light source.

APPENDIX 1: Taxonomy of microbial assemblages in Lake Thetis

The existing criteria for success are based on the microbes listed in Grey *et al*. (1990). This provides a sound basic structural and functional basis from which to view the microbial communities, namely:

i) the combined flocculent mat and massive organic matter rich sediment of the lake bed. This appears to play a background role in moderating the brine because it acts as a reservoir of both nutrients and sulfur which both influence alkalinity, and also the rate and volume of element cycling and consequently community dynamics, if not composition (Grey *et al*. 1990; Goh *et al*. 2009);

ii) the peripheral mats which experience varying degrees of exposure and include the nodular mats and the microbialites;

iii) the microbes of the water column.

This work does not reveal the full diversity of microbes, however, and is a weak basis from which to determine change in such diversity because it is largely based on visual identification of microbes, it reflects the state of taxonomy at the time, it lists only about 10 obvious and/or dominant species most of which are cyanobacteria and completely omits the domain archaea. In addition, the relationship of community variation between structures outlined is superficial.

There have been great advances in microbial biodiversity assessment (eg Goh *et al.* 2009) that mean that a combination of isolation by selective culture in tandem with genetic sampling and matching is providing a much broader picture of the microbial community. Genetic matching helps recognize more taxa and relationships more rapidly and with defined levels of certainty. The number of taxa being found by such work in locations such as Shark Bay is an order of magnitude greater than with microscopy or culture, and it reveals that cyanobacteria only account for about 5% of diversity in the community. It is becoming apparent from such work that community variation between types of domes is very high. Once a database founded on such work is established it can form a reference for change with time and for comparison with other sites.

At Lake Thetis it is therefore desirable that microbial diversity is outlined through using a full range of complementary techniques to isolate and define microbial taxa, and that sampling is targeted at key sub-sets of microbial communities as follows:

- the **nodular mats**, incorporating:
  - primarily the domes in the southwest and the platforms at the north, and more than one sample of each to allow for variation;
  - core criteria for failure in terms of the domal surface community need to then be determined from knowledge of the function of such taxa, and may be the loss of one or more faithful taxa (phylotype/ Operational Taxonomic Units - OTUs) of cyanobacteria (and/or sulphate reducing bacteria);
  - core criteria for failure in terms of the interior domal community need to then be determined from knowledge of the function of such taxa, and may be loss of two or more faithful taxa (phylotypes/ OTUs) of bacteria, especially sulphate-reducing and/or archaea;
- the **water body near the domes and the waterbody at the middle of the lake**, incorporating:
  - criteria for failure need to then be determined from knowledge of the function of such taxa and may be the loss of any faithful taxon from the cyanobacteria and/or a significant change in the eubacteria. This may be extended to include loss of a taxon from the archaea, if a means of concentrating and isolating them from the water column is determined;
- the **flocculant mat containing sulfur bacteria at the bottom of the lake basin**, incorporating:
  - core criteria for failure need to then be determined from knowledge of the function of such taxa and may be the loss of any one or more faithful taxa of:
    - surface film microbes such as the Oscillatorian cyanobacteria or non-phototrophic filamentous bacteria (eg microaerophilic H_2S-oxidiser *Beggiatoa* sp; see table 5 Grey *et al*. 1990);
    - upper sediment microbes, especially purple sulfur bacteria (anoxygenic, H_2S utilizing photosynthetic bacteria, *Thiocystis/Thiocapsa* group);
    - deep sediment microbes, especially filamentous bacteria (likely sulphate-reducing flexibacteria).

These data then allow the number of taxa and the diversity of archaea, eubacteria and cyanobacteria in each sub-set to be elucidated and compared. Comparisons can then be made between the different samples and also between them and Shark Bay material, especially cyanobacteria of the nodular mats. This sampling is recommended to be repeated initially at 5-10 year intervals (then ≥10 years) to monitor change over time. It is important to moderate the harm done by sampling, through closely confining the site and ensuring that the point can be relocated for any future monitoring. It is also important to limit the area of impact for example by taking a core, taking each survey as an opportunity to review and refine the target areas if feasible, and find less destructive ways of taking samples such as taking water column samples as surrogates for microbiolite samples at least at alternate sample times. The relationship between surrogates and microbiolite samples would need to be established over time, primarily in terms of composition, and secondarily in terms of abundance.

The above will need to be carefully qualified by clarification of the influence of relic or ancient DNA on the sequences extracted and comparisons made. Other factors to be considered will include the role that spores play in the persistence of taxa when communities appear to be inactive. It is important to determine the interval after which spores will fail to reconstitute the community. The evidence of recent change in the structure and composition of the bioherms, suggesting large parts of the existing bioherms grew under different conditions from today (Reitner *et al*. 1996). The current outer layer is calcified microbial mat dominated by '*Entophysalis*' and is a few millimetres thick. Before that the more substantial layers underneath are *Scytonema*-dominated carbonates. The issues to be considered include the date of the change and if the exchange between these layers is contemporary and if the lower layer still harbors an active community. The indicators that the environmental conditions such as lake level and hydrochemistry have changed need to be determined.

The success criteria could also incorporate reference to changes to the brine including indicators of short-term human-induced change such as surplus nutrient input which has the potential to alter the microbial community and adjust the alkalinity. Pesticides and other manufactured chemicals should also be considered in success criteria. This has the potential to alter the microbial community and adjust the alkalinity.

Three features with a long-term emphasis, that are fairly resistant to change, and which would act as indicators of catastrophic flux, are change in the relative ratio of dominant ions, which are usually characteristic and stable in the medium-term despite fluctuations in the overall concentration. In a sea brine this is reflected by Na^+, Mg^{2+}, Ca^{2+}, K^+, Cl^-, and SO_4^{2-}. Other significant changes would include change in the alkalinity and the buffering capacity of the system, and a change to the mixing characteristics of the lake. At present the lake appears to be well mixed.

APPENDIX 2: Water measurements in Lake Thetis

The following issues need to be considered when sampling hypersaline brines such as in Lake Thetis. It will be important to ensure that concurrent field measurements and samples are taken.

Marine brines are not suited to terrestrial freshwater sampling techniques, and there should be ongoing refinement and selection of sampling and analysis work that has been tailored to suit the concentrated nature of the brine.

Water chemistry sampling at Lake Thetis has not been consistent in the past, and a methodical approach is desirable in future. A reasonably comprehensive set of parameters has been developed and will be used as the basis for future sampling analysis. In combination with a less intensive set of such data dating back to 1985 it may provide an indication of what changes have occurred in the brine. The only major ingredients not sampled are metals such as aluminium.

Laboratory analysis of brine chemistry may provide indicators of the lake's status as follows:

- Apart from pH, there are three potential estimates of salinity, namely: a) absolute salinity from the sum of the constituents; b) by conversion from conductivity; and c) an approximation from the TDS measure.

- The main components of Total Alkalinity.

- Several parameters can be used as inputs to reflect the CO_2 system and so calculate underlying $CaCO_3$ saturation and related factors.

- Potential gross indicators of the level of activity of groups of bacteria such as sulfates for sulphur-metabolising bacteria and possibly ammonia/ammonium for nitrogen-metabolising bacteria if other components can be quantified, especially terrestrial input due to fixation, and biomass in the water column.

- Some indication of biomass from organic carbon, without regard for separating live and dead matter

- Nutrient (N, P and S) and carbon cycle components.