



RANGELANDS
NRM CLUSTER



IMPACTS & ADAPTATION
I N F O R M A T I O N
FOR AUSTRALIA'S NRM REGIONS



Australian rangelands and climate change – aquatic refugia



Citation

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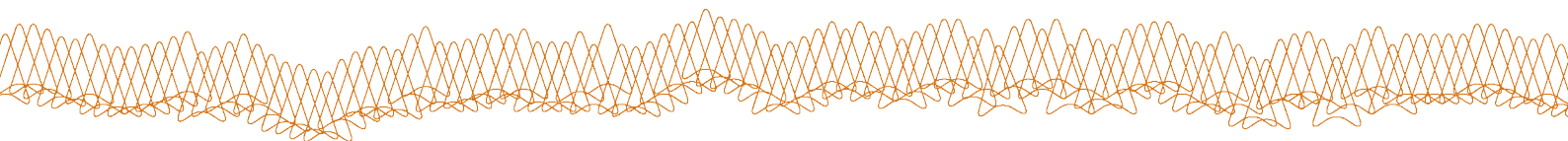
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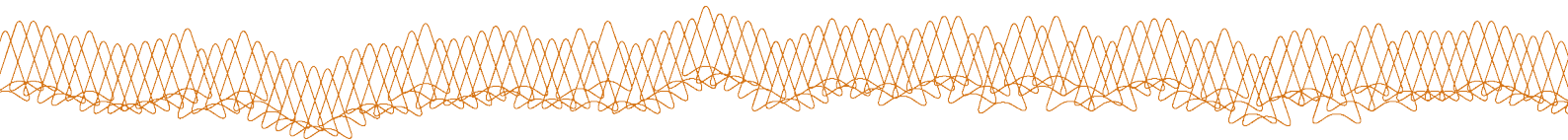


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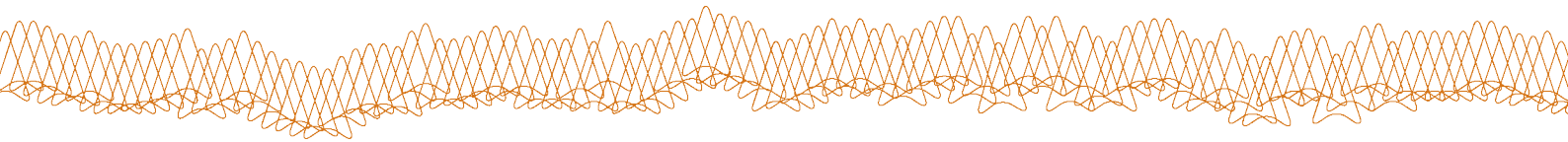


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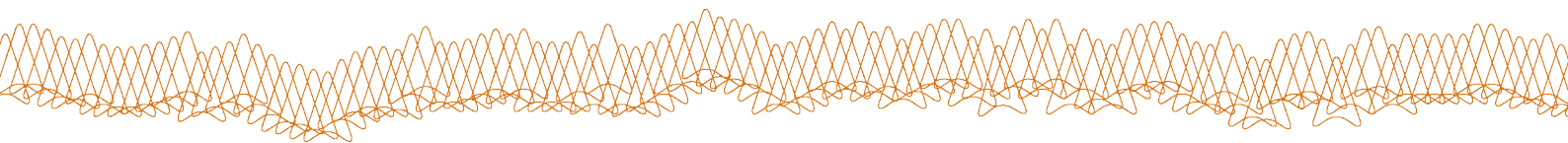
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Key points

- The NRM Rangelands Cluster region is highly water-limited, and all water (surface and groundwater) in the region is environmentally, culturally and economically important. Given that water scarcity is likely to continue under all climate change scenarios, the identification, management and restoration of aquatic refugia is a critical adaptation strategy for rangelands ecosystems and the biota they support.
- Refugia are defined as habitats that biota retreat to, persist in and potentially expand from under changing environmental conditions. Different types of refugia are important for different species over differing spatial and temporal scales. Two major types of refugial habitats are recognised: evolutionary refugia and ecological refuges.
- Evolutionary refugia are defined as those waterbodies that contain short-range endemics (species that occur only within a very small area) or vicariant relicts (species with ancestral characteristics that have become geographically isolated over time). Although these species often have very small geographical ranges, their populations are relatively stable and high levels of genetic diversity are present. All aquatic evolutionary refugia in the NRM Rangelands Cluster regions are groundwater-dependent ecosystems. Evolutionary refugia are most likely to persist into the future and should be accorded the highest priority in NRM adaptation planning.
- Ecological refugia are defined according to the water requirements of the species they protect. Obligate aquatic organisms (fishes and some aquatic invertebrates that can only disperse via water) need perennial (permanent) aquatic habitats, or closely located near-perennial habitats, to ensure persistence. In contrast, important ecological refugia for waterbirds are the large temporary or ephemeral freshwater lakes and salt lakes that hold water after infrequent but large episodic rainfall events. The conservation significance of ecological refugia, and the priority assigned to their conservation, depends on the level of knowledge available for the species they support. Information regarding species characteristics, such as dispersal traits, is particularly important for the determination of the importance of ecological refugia. Highly mobile species are less likely to be dependent on perennial systems.
- The vulnerability of aquatic refugia to climate change is influenced by their source of water (groundwater or surface water). Those waterholes that depend primarily on rainfall (surface water) for their water supply are highly sensitive, and those that depend primarily on discharge from groundwater (either regional or local) systems are the least sensitive, because of the great buffering capacity of groundwater, both hydrologically and thermally. The climate adaption capacity of aquatic species in the rangelands is influenced by their habitat requirements and their dispersal ability. Short-range endemics and relictual species have limited capacity to recolonise waterbodies that dry out and so these species are at the greatest risk of extinction, particularly from the indirect impacts of climate change.
- The indirect effects of climate change, particularly an increase in human demands for water (for direct consumption and production of food, fibre and energy) are likely to have greater impacts than direct climatic effects. Excessive groundwater drawdown will destroy spring-based evolutionary refugia, and the construction of surface water impoundments will destroy the aquatic connectivity essential for the persistence of riverine waterholes as ecological refugia. The existing adverse impacts of livestock, feral herbivores, invasive fishes, exotic plants, recreation and tourism must also be managed.
- Tools for NRM adaptation planning provided in this report include a list of priority aquatic refugia (sites likely to act as future refugia) and a decision support tree. The latter will aid the identification of major types of waterbodies and the refugia they provide, vulnerability assessments and development of management responses to address direct and indirect climate impacts and other stressors. A site register of important rangelands aquatic refugia is provided at Appendix A. This is regarded as a 'living' register that should be updated as more information becomes available.



1. Introduction

Water scarcity, highly variable annual precipitation and high rates of potential evapotranspiration are defining characteristics of the Australian rangelands. Climate projections for the Rangelands Cluster region indicate that high natural rainfall variability will continue and may mask trends in average rainfall for some decades to come, particularly for summer rainfall. The intensity of extreme rainfall events will increase; average summer rainfall may change in some regions, but the median change is likely to be small relative to natural variability. Winter rainfall is likely to decline in both the north and south. Potential evapotranspiration is projected to increase in all seasons, most strongly in summer.

In water-limited environments such as the rangelands, all natural waterbodies are environmentally, culturally and economically valuable. Accordingly, one of the most important climate adaptation strategies for the NRM Rangelands Cluster is the identification, management and restoration of aquatic refugia.

1.1 What are refugia?

Refugia are habitats that biota retreat to, persist in and potentially expand from under changing environmental conditions (Keppel et al. 2012). Two major types of arid zone refugial habitats, evolutionary refugia and ecological refuges, were defined by Davis et al. (2013). However, Reside et al. (2014) suggested that the term 'refuge' should only be applied to habitats that shelter individuals from short-term disturbances, while 'refugia' describes habitats that provide protection to populations or species over ecological or evolutionary timescales. To avoid confusion, this report uses only the term 'refugia'. However, the distinction that Davis et al. (2013) made between evolutionary and ecological refugial habitats remains important for prioritising conservation measures as part of climate adaptation planning. For this reason, guidance for the identification of both evolutionary refugia and ecological refugia forms a major part of this report.

1.2 Direct vs. indirect climate change impacts on aquatic refugia

All freshwater ecosystems are vulnerable to climate change because of their relative isolation and physical fragmentation within terrestrial landscapes (Woodward et al. 2010). These factors mean that many aquatic species will have limited ability to disperse as temperatures increase and previously perennial waterbodies become temporary or ephemeral. However, it is the potentially large, indirect effects of increasing human demands for water that are likely to have even greater impacts on freshwater ecosystems (Palmer et al. 2008). A rising global population means that there will be an ever-increasing demand for water for domestic consumption and the production of food. This demand, occurring in concert with a warming and drying climate, suggests that there will be intense competition for water between human and environmental needs. This competition will be exacerbated in arid and semi-arid landscapes of the rangelands. Indirect effects include the depletion of aquifers and lowering of water tables caused by increasing extraction of groundwater. Mine dewatering will have a similar impact. Connectivity along river networks will be disrupted through the construction of dams and an increase in river offtakes for irrigation. The likely severity of impacts means that assessing the vulnerability of refugia to both direct and indirect effects is an important part of climate adaptation planning.

2. Methods

This project was undertaken primarily as a desktop study. It builds on previous work on arid and semi-arid zone refugia described by Davis et al. (2013) and information relating to rangelands sub-regions as listed in Table 2.1.

Table 2.1 Aquatic refugia data sources listed by Rangelands Cluster sub-region

| REGION | DATA SOURCES |
|---------------------|--|
| Alinytjara Wilurara | Nathanael Wiseman ([Researcher, Geography, Environment and Population, The University of Adelaide] 2014, pers. comm., 23 April) |
| Desert Channels NRM | Silcock (2009) |
| Rangelands WA | Pinder et al. (2010) Adrian Pinder ([Principal Research Scientist, Department of Parks and Wildlife, WA], 2014, pers. comm., 9 September) |
| SA Arid Lands | Costelloe & Russell (2014) McNeil et al. (2011) Jackie Watts ([Monitoring, Evaluation and Reporting Officer, Natural Resources, SA Arid Lands, Adelaide] 2014, pers. comm., 15 April) Nick Murphy ([Lecturer, Genetics Department, La Trobe University, Melbourne] 2014, pers. comm., 3 June) |
| South West NRM | Silcock (2009) |
| Territory NRM | Duguid et al. (2005) |
| Western CMA | |
| National | Morton et al. (1995) Directory of Important Wetlands (Environment Australia 2001) |

3. Findings

3.1 Identifying aquatic refugia

3.1.1 Evolutionary refugia

These are perennial freshwater ecosystems that have supported aquatic species over millions of years. Identification of evolutionary refugia requires knowledge of the species (plants, aquatic invertebrates and fishes) that they support. Most importantly, waterbodies are considered to be evolutionary refugia if they contain short-range endemics (species that occur only within a very small area) or vicariant relicts (species with ancestral characteristics that have become geographically isolated over time). Although these species often have very small geographical ranges, their populations are relatively stable and high levels of genetic diversity are present. All aquatic evolutionary refugia in the NRM Rangelands Cluster region are groundwater-dependent ecosystems. This is not surprising, given that groundwater is the only source of water within arid Australia that has persisted over millennial timescales.

3.1.2 Ecological refugia

The most important ecological refugia in the NRM Rangelands Cluster region are perennial and near-perennial waterbodies supported by groundwater, surface water or a combination of both. These systems are governed by the boom and bust dynamics described by Kingsford et al. (1999), Bunn et al. (2006) and others. The identification of an ecological refuge varies depending on the characteristics, particularly the dispersal abilities, of the species of concern. Obligate aquatic organisms (fishes and some aquatic invertebrates) need perennial habitats, or closely located near-perennial habitats, to ensure persistence. Perennial systems are also important for the persistence of terrestrial species such as bats and some snakes and amphibians. Waterbirds, which can disperse aerially over long distances, can use a mosaic of temporary wetlands over broad spatial scales (Roshier et al. 2001).

Table 3.1 Major types of rangeland aquatic ecosystems and their water sources.

| NAME | WATER SOURCE | DESCRIPTION |
|-------------------------------------|--------------|---|
| Subterranean aquifers | GW* | Shallow, underground carbonate habitats in the central region of WA and in WA palaeo-river channels. Sites within fractured rock aquifers in the Pilbara region. Sites within alluvial aquifers in north-east Australia. Characterised by permanent water, no light and therefore no primary production. |
| Discharge (mound) springs | GW | Surface expressions of the Great Artesian Basin (GAB). Characterised mainly by permanent and consistent flows and alkaline waters with high concentrations of dissolved solids. Clustered at a range of scales, from individual vents to spring complexes to 13 major 'super-groups.' Discharge springs are also present outside the GAB, e.g. Mandora Marsh in north-west Australia. |
| Outcrop springs | GW | Mainly arise from local fractured rock (sandstone, limestone or quartzite) aquifers and are usually located near the base of ranges. Slightly acidic and very fresh. Usually permanent, although some can contract and sometimes dry completely. |
| Relict streams | GW | Small, permanently flowing sections of streams in the headwaters of the rivers of the Central Ranges, supported by outcrop springs. Cool, mesic-type habitats, mostly within deeply shaded, south-facing gorges. Called 'relict streams' because they support stream-dwelling insects with Gondwanan affinities. |
| Riverine waterholes | SW*/GW | Permanent, temporary or ephemeral waterbodies present in dryland river networks. Connected when large but infrequent rain events result in high flows or flooding; disconnected and reduced in area and depth when flows cease, except for hyporheic (below surface) flows. Waterholes in the eastern Lake Eyre Basin (LEB) are often turbid; those in the western LEB and the Pilbara are often clear. Often surface water-fed, but some permanent waterholes may receive groundwater/hyporheic flows. The latter includes the large waterholes on the Finke River (Running Waters and Boggy Hole) and nearly all permanent river pools in the Pilbara region. |
| Stream pools/rockholes | SW | Pools or rockholes in small, rocky headwater creeks within arid zone ranges. Fed by local rainfall events, they are usually temporary or ephemeral. |
| Isolated rockholes/gnammas | SW | Water stored in natural hollows formed by fracturing and weathering of rocky landscapes. Fed by local runoff from infrequent rainfall events. Small and isolated habitats that are widespread, but not abundant, throughout the arid zone. Also called gnammas. Mainly temporary or ephemeral systems. |
| Temporary lakes, swamps and marshes | SW | Isolated, shallow basins, not in watercourses, fed by local runoff after infrequent rain events. These include interdunal systems within desert dune regions and extensive floodplains (e.g. in LEB). Hydroperiods are highly variable and unpredictable. The distinction between lakes, swamps and marshes can be arbitrary, but the latter two usually refer to vegetated systems. |
| Clay pans | SW | Temporary, shallow basins with an impervious base fed by local runoff and dominated by evaporative processes. They contain fresh and characteristically turbid water when fed by local run-off after infrequent rain events or left behind as flood waters recede. Hydroperiods are short, highly variable and unpredictable. |
| Salt lakes/saline playas | SW/GW | Temporary, shallow basins fed by SW and/or GW (depending on site). They are characterised by highly episodic hydroperiods, high salinities and clear water. Highly productive systems when water is present. |
| Soaks | GW | Sub-surface systems that support groundwater-dependent plant communities but do not have free surface water. |

Source: Davis et al. 2013

* GW = groundwater, SW = surface water

3.2 Refugia provided by different types of waterbodies

A typology of rangeland waterbodies has been developed to support the assignment of refugial status (Table 3.1). The typology used here (from Davis et al. 2013) extended the work of Fensham et al. (2011) who recognised four types of permanent waterbodies: riverine waterholes, rockholes, discharge springs and outcrop springs, in the eastern Lake Eyre Basin (LEB). Their typology was based on the major geomorphic attributes of these systems, which, being fixed or structural attributes of geology and landform, are much less variable than water quantity or quality. The typology developed for the eastern LEB was extended to include all types of waterbodies across the NRM Rangelands Cluster region.

Three types of perennial waterbodies, all groundwater-dependent ecosystems, have been identified as evolutionary refugia, based on the presence of endemic and relictual species, by Davis et al. (2013). These are subterranean aquifers, discharge (Great Artesian Basin mound) springs and relict streams. Some perennial riverine waterholes may also act as evolutionary refugia, but more phylogenetic information is needed to confirm their value as evolutionary refugia (Table 3.2).

Table 3.2 Timescales of evolutionary refugia inferred from phylogenetic studies

| WATERBODY | TIME |
|----------------------------------|---|
| Subterranean aquifers | Mid-Miocene, 3–11 mya |
| Mound springs, GAB | 2.5–0.4 mya |
| Relict streams/ local springs | LGM*, 18,000 yrs |
| Riverine waterholes | Pleistocene, LGM to present (depending on taxon) |

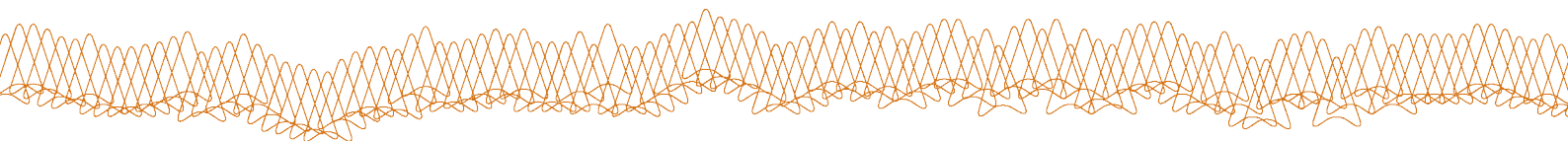
Source: Davis et al. 2013
*LGM = Last Glacial Maximum

Most perennial and near-perennial waterbodies, either groundwater or surface water-fed, are likely to act as ecological refuges. These systems provide ‘reservoirs’ to which species contract during dry periods and droughts and disperse from during wetter phases.

Refugia provided by different types of waterbodies are listed in Table 3.3.

Table 3.3 Summary of refugia provided by different types of waterbodies and suggested priority for protection of specific biota based on current information

| NAME | TYPE OF REFUGIA | PRIORITY FOR PROTECTION BASED ON CURRENT INFORMATION |
|-------------------------------------|-----------------------------|---|
| Subterranean aquifers | Evolutionary | Very High for protection of endemic species (stygo fauna) |
| Discharge (mound) springs | Evolutionary and Ecological | Very high for protection of endemic species of plants, fishes and invertebrates |
| Outcrop springs | Ecological | Medium |
| Relict streams | Evolutionary and Ecological | Very high for protection of relict species of invertebrates |
| Riverine waterholes | Evolutionary and Ecological | Very high at perennial waterholes for protection of regionally endemic species (fishes and invertebrates) |
| Stream pools/rockholes | Ecological | Medium |
| Isolated rockholes/gnammas | Ecological | Medium ; dry sediments act as refugia for egg and seed banks. Note: these waterbodies may have very high cultural significance |
| Temporary lakes, swamps and marshes | Ecological | Very high when wet for protection of waterbirds; dry sediments act as refugia for egg and seed banks |



| NAME | TYPE OF REFUGIA | PRIORITY FOR PROTECTION BASED ON CURRENT INFORMATION |
|--------------------------|-----------------|--|
| Clay pans | Ecological | Medium ; sediments act as refugia for egg and seed banks |
| Salt lakes/saline playas | Ecological | Very high when wet for protection of waterbirds; dry sediments act as refugia for egg and seed banks |
| Soaks | Ecological | Very high to Medium , based on conservation significance of groundwater-dependent vegetation supported by sub-surface water |

3.3 Stepping stones

Temporary and ephemeral aquatic habitats potentially play important roles as ‘stepping stones’ between perennial sites. They can also provide extra resources that enable populations to increase, reproduce and replenish egg and seed banks during wet phases (booms). However, with the exception of the research on the role of temporary wetlands as waterbird habitats by Roshier et al. (2001), the exact role of non-perennial systems as stepping stones or intermediate spatial refugia is not well understood. How extensive and how closely located systems must be to act as stepping stones are two questions that need to be answered to inform conservation planning. This is an important research gap that needs to be addressed in the near future. Despite this lack of knowledge, it is clear that protecting a dynamic (spatial and temporal) mosaic of perennial, temporary and ephemeral waterbodies across the rangelands is needed to support the persistence of aquatic and water-dependent species with varying life history traits and dispersal abilities.

3.4 Sediments as refugia

The importance of the sediments of non-perennial freshwater lakes, clay pans, salt lakes and rockholes as temporal refugia is well established (Brendonck & De Meester 2003). The seed and egg banks present in the sediments of these systems act as biotic reservoirs. Protecting the integrity of the sediments of non-perennial systems is clearly important. However, the spatial scales at which protection will be most useful still need to be determined.

3.5 Prioritising aquatic refugia for climate adaptation planning

Different types of waterbodies provide refugia for different components of the rangelands aquatic and, in some cases, terrestrial biota. Rather than prioritising refugia based only on their evolutionary and ecological value, which can be difficult to ascertain given the lack of information for many ecosystems in the NRM Rangelands Cluster region, a prioritisation has been developed that combines both biological knowledge and the level of confidence (high, medium and low) of this knowledge for one or more biotic groups (Table 3.4). Note that refugia currently listed as Conservation Priority 2 could move to Conservation Priority 1 as more information becomes available.

3.6 Distribution of aquatic refugia by NRM Rangelands Cluster sub-regions

The distribution of aquatic refugia varies considerably across the rangelands. A register listing the locations of aquatic refugia within the NRM Rangelands Cluster Sub-Regions is provided at Appendix A. The sites included in this register are based on current information and should be updated as more information becomes available over time.

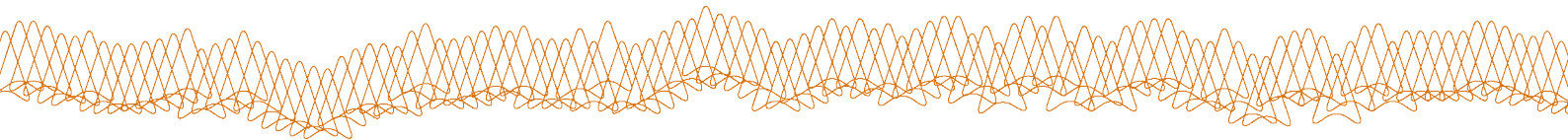


Table 3.4 Conservation priority assigned to aquatic refugia based on the level of confidence of knowledge of the importance of the waterbody to specific biota

| CONSERVATION PRIORITY 1 – HIGH CONFIDENCE | |
|--|---|
| Evolutionary refugia (fishes, aquatic invertebrates and plants) | |
| (a) Subterranean aquifers | <i>All calcrete aquifers in the mid-west of WA</i> <i>Palm Valley aquifer, NT</i> |
| (b) Discharge (mound) springs | <i>Mound springs in the GAB: SA, NT, NSW, Qld</i> |
| (c) Relict streams | <i>Groundwater-fed headwaters of rivers in the Central Ranges, NT</i> |
| (d) Spring-fed streams | <i>Spring-fed streams of the Pilbara-Hamersley Ranges WA (as identified by Pinder et al. 2010) – see Appendix A</i> |
| Ecological refugia (fishes and waterbirds) | |
| (d) Perennial waterholes | <i>Riverine waterholes of the LEB with cease-to-flow depths > 4 m (as mapped by Silcock 2009)</i> <i>Riverine waterholes of the Pilbara-Hamersley Ranges WA (as identified by Pinder et al. 2010)</i> |
| Ecological refugia (waterbirds) | |
| (e) Large temporary lakes (freshwater and salt) in the LEB, including Lake Eyre and Lake Torrens, SA | <i>Lake Gregory, Mandora Marshes, WA</i> |
| CONSERVATION PRIORITY 2 – MEDIUM TO LOW CONFIDENCE | |
| Ecological refugia (waterbirds) | |
| (f) Non-perennial riverine waterholes in river networks in: | <i>the LEB: NT, SA, Qld, NSW</i> <i>Pilbara-Hamersley Ranges, WA</i> <i>Flinders Ranges, SA</i> |
| Ecological refugia (aquatic invertebrates) | |
| (g) Sediments of freshwater lakes, salt lakes, claypans, rockholes and gnammas: continental distribution | |

3.7 Vulnerability assessments

The vulnerability of aquatic refugia to climate change falls between two extremes: those dependent primarily on rainfall for their water supply are highly vulnerable, and those dependent primarily on discharge from groundwater (either regional or local) systems are the least vulnerable, because of the great buffering capacity of groundwater systems to thermal and hydrological change. However, the situation is not as simple as this statement suggests. Climate change impacts, although important, are not the only impacts affecting rangelands aquatic refugia. Other stressors, including indirect climate impacts on water availability (groundwater drawdown and surface water impoundments) and the impacts of livestock, feral herbivores, invasive fishes, exotic plants, recreation and tourism must also be considered.

Although groundwater-fed evolutionary refugia are well buffered from a local decrease in rainfall, the endemic and relictual species they support are highly sensitive to changes in local conditions. The absence of water and habitat degradation will result in population declines, and, ultimately, extinction because populations cannot be ‘rescued’ by dispersal of individuals from other sites. In contrast, the species present in ecological refugia are well adapted to ‘boom and bust’ cycles. These species will persist where suitable habitats are available and dispersal pathways are maintained. They have dispersal mechanisms that facilitate metapopulation dynamics and gene flow over larger spatial scales. Maintaining connectivity by mitigating barriers to dispersal and alterations to the natural flow regime are important management strategies for obligate aquatic species such as fish.

A vulnerability assessment can help identify whether refugia are likely to be affected by direct and indirect climate impacts and other stressors and provides a framework for understanding why systems are likely to be vulnerable (Glick et al. 2011). Vulnerability is a function of exposure to climate change: the magnitude, intensity and duration of the changes experienced; the sensitivity of the species or community to these changes; and the capacity of the system to adapt (IPCC 2007, Williams et al. 2008). Vulnerability assessments

can be an important part of the process supporting identification and prioritisation of climate adaptation strategies.

A recent Ramsar report (Gitay et al. 2011) provided a framework for assessing the vulnerability of wetlands to climate change. This framework can be used to assess the vulnerability of aquatic refugia in the rangelands. The processes that need to be followed are listed in Figure 3.1. These include a) establishing present status and recent trends; b) determining sensitivity and

adaptive capacity to multiple pressures; c) developing responses; and d) the need for monitoring and adaptive management to ensure that desired outcomes are achieved. This type of approach emphasises the need for developing and implementing responses that will help reduce the vulnerability of refugia. One major qualifier, however, is that climate change is not the only driver of change that aquatic refugia are likely to experience or already experience.

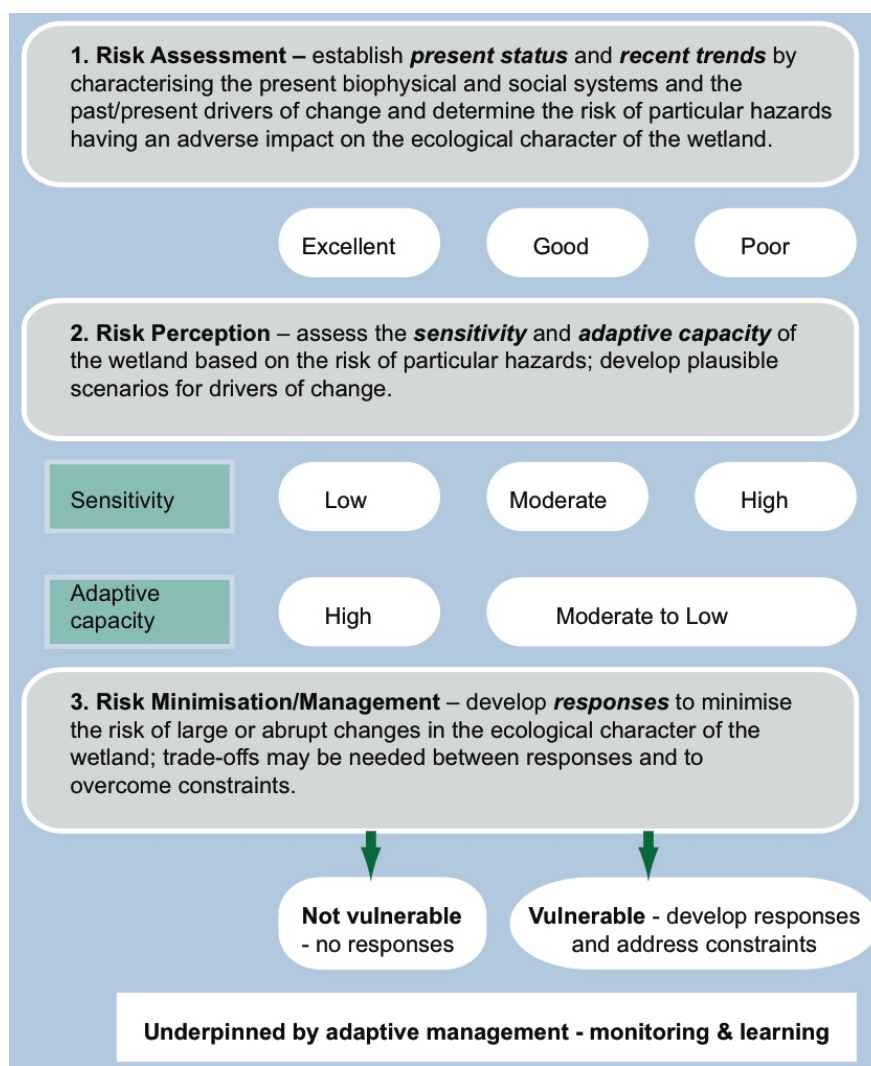
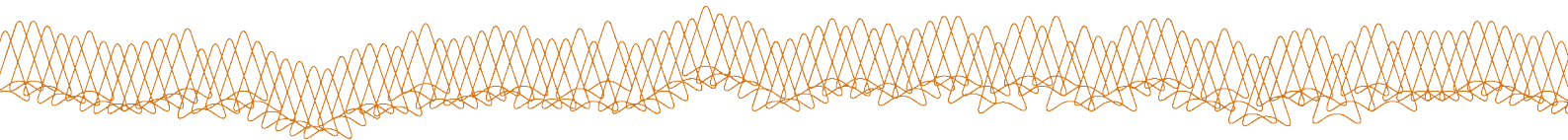


Figure 3.1 A vulnerability assessment framework for Ramsar wetlands that has application for aquatic refugia

Source: Gitay et al. (2011)



The application of this framework to aquatic refugia is demonstrated by the case study provided in the following box.

Vulnerability assessment: Dalhousie Springs

Description: Supergroup of ~80 active GAB springs, Witjira National Park, SA

1. Risk assessment

Present status

Springs are classified as evolutionary refugia because they contain short-range endemics. Biodiversity conservation value is very high. Springs are protected within a declared conservation area (Witjira National Park).

2. Risk perception

Sensitivity

Low to direct climate impacts because springs are groundwater-fed (GAB). **Very High** to indirect climate impacts (groundwater extraction) and other stressors (degradation of habitat and poor water quality due to impacts of livestock and feral herbivores, predation pressure from exotic fish, invasion by exotic plants).

Adaptive capacity

HIGH for habitat, **LOW** for endemic biota because although springs are buffered from direct climate impacts by groundwater, endemic spring biota have little capacity to recolonise if springs run dry.

3. Risk minimisation/management

Vulnerability

Direct climate impacts: **LOW**

Indirect climate impacts and other stressors: **VERY HIGH**

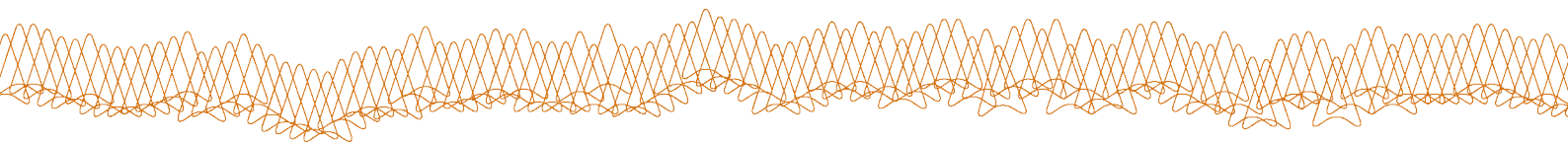
Risk minimisation / Adaptation strategy

Protect aquifer and monitor water levels in key springs. Fence or add alternative watering points to reduce impacts of livestock and feral herbivores. Restore degraded habitats. Assess new developments for potential impacts on springs and the aquifer supporting them.

3.8 Decision tree to support climate adaptation planning to protect aquatic refugia in the NRM Rangelands Cluster region

The following decision tree has been developed to provide guidance for adaptation planning for NRM Rangelands Cluster aquatic refugia.

1. Classify type of waterbody (use Table 3.1)
↓
2. Identify type of refugium provided by the waterbody and the suggested protection priority. This can be done by using Tables 3.3–3.4 or from first principles based on information on the water source (groundwater or surface water), water regime (perennial or temporary) and the attributes of species (particularly dispersal traits) recorded at the waterbody.
↓
3. Undertake a vulnerability analysis (use Figure 3.1) to determine both direct and indirect impacts of climate change and other stressors (see case study for example).
↓
4. Develop an adaptation action plan based on risks and impacts identified by vulnerability analysis and conservation priority list.
↓
5. Assess new proposals (e.g. mining and energy extraction approvals, groundwater extraction, surface water impoundments and offtakes) to ensure that future vulnerability is minimised.
↓
6. Apply climate adaptation plan within an adaptive management program. Actions include monitoring water availability (continuous depth logging, where possible), monitoring habitat condition and persistence of key species, at regular intervals (annual) and with regular review (5 years). Implement restoration activities at degraded refugial sites.



4. Knowledge gaps

New waterbodies produced by rangelands industries – for example, dewatering by mines and watering points on pastoral stations – may potentially have some refugial values. However, they may also have negative effects on flora and fauna (James et al. 1999, Fensham & Fairfax 2008). The role that such waterbodies may play in off-setting the loss of ecological refugia through climatic drying needs to be determined. Further research is needed to ascertain the refugial value of artificial waterbodies in the context of a warming and drying climate.

5. Synthesis

Water scarcity, created by low and highly variable annual rainfall and high rates of evaporation and evapotranspiration, is a defining feature of the NRM Rangelands Cluster region. Given that water scarcity is predicted to continue under all climate change scenarios, the identification, management and restoration of aquatic refugia is a critical adaptation strategy for rangelands waterbodies and the biota they support.

Refugia are defined as habitats that biota retreat to, persist in and potentially expand from under changing environmental conditions. Two major types of refugial habitats are recognised: evolutionary refugia and ecological refugia. All aquatic evolutionary refugia in the NRM Rangelands Cluster regions are groundwater-dependent ecosystems. They are defined as waterbodies that contain short-range endemics (species that occur only within a very small area) or vicariant relicts (species with ancestral characteristics that have become geographically isolated over time). Evolutionary refugia are most likely to persist into the future because their source of water is independent of local rainfall. They should be given the highest priority in NRM adaptation planning.

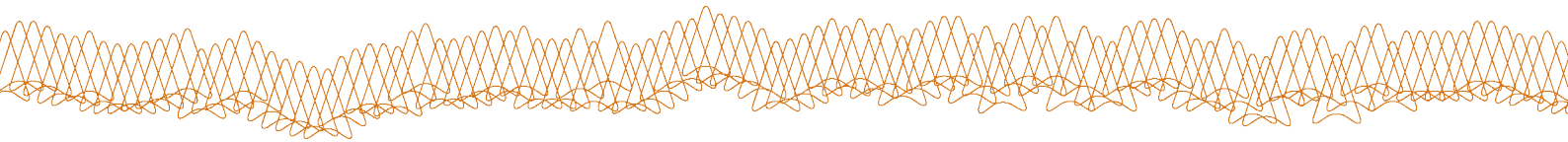
Ecological refugia are defined according to the aquatic requirements of the species they protect. Obligate aquatic organisms (fishes and some aquatic

invertebrates which can only disperse via water) need perennial habitats, or closely located near-perennial habitats, to ensure persistence. Important ecological refugia for waterbirds are the large temporary or ephemeral freshwater lakes and salt lakes that hold water after infrequent but large episodic rainfall events. The conservation significance of ecological refugia, and the priority assigned to their conservation, depends on the level of knowledge available for the species they support. Highly mobile species are less likely to be dependent on perennial systems than obligate aquatics.

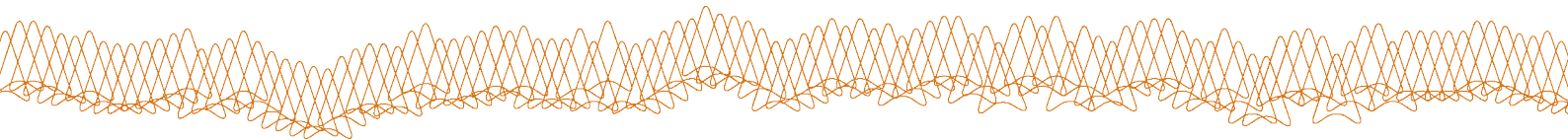
The vulnerability of aquatic refugia to climate change is influenced by their source of water (groundwater or surface water). Those waterholes that depend primarily on rainfall (surface water) for their water supply are highly sensitive, and those that depend primarily on discharge from groundwater (either regional or local) systems are the least sensitive, because of the great buffering capacity of groundwater, both hydrologically and thermally. The climate adaption capacity of aquatic species in the Rangelands is influenced by their habitat requirements and their dispersal ability. Short-range endemics and relictual species have limited capacity to recolonise waterbodies that dry out and so these species are at the greatest risk of extinction, particularly from the indirect impacts of climate change.

It is important to recognise that the indirect effects of climate change, particularly an increase in the demand for water for direct consumption and production of food, fibre and energy, may have a greater negative impact on aquatic ecosystems than direct climatic effects. Excessive groundwater drawdown will destroy spring-based evolutionary refugia and the construction of surface water impoundments will destroy the aquatic connectivity essential for the persistence of riverine waterholes as ecological refugia. The existing impacts of livestock, feral herbivores, invasive fishes, exotic plants, recreation and tourism also need to be managed in the context of a changing climate.

This report provides some tools for NRM adaptation planning. These include a list of priority aquatic refugia (sites likely to act as future refugia) and a decision support tree to guide decision-making. Suggested actions include the identification of major types of waterbodies and the refugia they provide, vulnerability



assessments and development of management responses to address both direct and indirect climate impacts. A site register of important rangelands aquatic refugia is provided at Appendix A. This is a 'living' register that needs to be updated as more information becomes available.



Appendix A List of permanent aquatic refugia (evolutionary and ecological) in the NRM Rangelands Cluster Region

In the accompanying zip file at http://www.nintione.com.au/resource/AustralianRangelandsAndClimateChange_AquaticRefugia_RegisterAquaticRefugia.zip, there are 15 lists of permanent aquatic refugia (evolutionary and ecological) in the NRM Rangelands, which have been compiled from the information on permanent waterbodies provided by Silcock (2009) for the eastern Lake Eyre Basin and Fensham et al. (2007) for the Great Artesian Basin mound springs. In addition, expert knowledge has been used to identify refugia in the WA Rangelands by Adrian Pinder (Department of Parks and Wildlife), for the SA Arid Lands (Lake Eyre South mound springs) by Dr Nick Murphy (Latrobe University) and for the NT Arid Lands sub-region by Professor Jenny Davis. These lists are not complete, and further refugia should be added as more information becomes available. No permanent waterbodies have yet been identified for the Alinytjara Wilurara region. Nor have sites been entered for the Tablelands sub-region of the NT.

The files included in the zip file are as follows:

- Desert Channels _Outcrop Springs Ecological Refugia.xlsx
- Desert Channels Coopers Ck Ecological Refugia.xlsx
- Desert Channels Diamantina Ecological Refugia.xlsx
- Desert Channels GAB Springs_Fensham et al.(2007).xlsx
- Desert Channels Georgina Ecological Refugia.xlsx
- Desert Channels LEB GABsprings_ Evolutionary Refugia (Silcock, 2009).xlsx
- Desert Channels Permanent_Rockholes_Ecological Refugia.xlsx
- NT Arid Lands Ecological Refugia.xlsx
- NT Arid Lands Evolutionary Refugia.xlsx
- SAAL GAB Mound Springs Evolutionary Refugia_Nick Murphy.xlsx
- SAAL GAB Mound Springs_Evolutionary Refugia_Fensham et al (2007).xlsx
- SW QLD GAB Springs Evolutionary Refugia.xlsx
- WA Rangelands Aquatic Refugia Coordinates.xlsx
- Western NRM.docx
- Western NRM.xlsx

Abbreviations

| IN THIS REPORT | |
|----------------|-----------------------------|
| TERM | DEFINITION |
| GAB | Great Artesian Basin |
| GW | Groundwater |
| LEB | Lake Eyre Basin |
| NRM | natural resource management |
| SW | Surface water |

| IN ALL REPORTS IN THE SERIES | |
|------------------------------|---|
| TERM | DEFINITION |
| ABS | Australian Bureau of Statistics |
| ACRIS | Australian Collaborative Rangelands Information System |
| AFCMP | Australian Feral Camel Management Project |
| BoM | Bureau of Meteorology |
| BS | bare soil |
| CMA | Catchment Management Authority |
| DKCRC | Desert Knowledge Cooperative Research Centre |
| DSI | Dust Storm Index |
| EI | Ecoclimatic Index |
| EMU | Ecosystem Management Understanding™ |
| ENSO | El Niño Southern Oscillation |
| FIFO | fly in, fly out |
| GCM | General Circulation Model |
| GDM | Generalised Dissimilarity Modelling |
| GHG | greenhouse gas |
| GWW | Great Western Woodlands |
| IBRA | Interim Biogeographic Regionalisation for Australia |
| ICLEI | International Council for Local Environmental Initiatives |
| IPCC | Intergovernmental Panel on Climate Change |
| LGM | last glacial maximum |
| MOF | manual observation frequency |
| mya | million years ago |

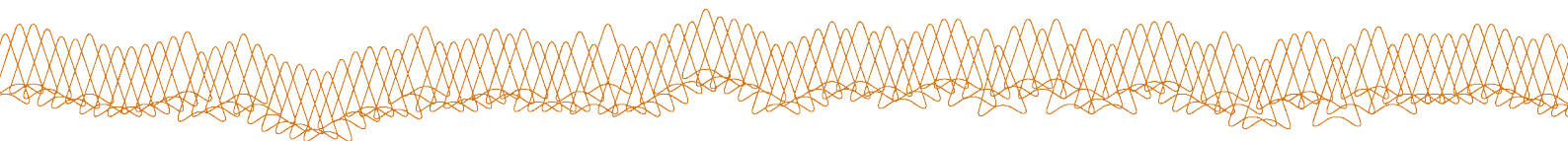
| IN ALL REPORTS IN THE SERIES | |
|------------------------------|---|
| TERM | DEFINITION |
| NAFI | North Australian Fire Information |
| NCCARF | National Climate Change Adaptation Research Facility |
| NPV | non-photosynthetic vegetation: senescent pasture and litter |
| OH&S | occupational health and safety |
| PV | photosynthetic vegetation: green |
| RCP | Representative Concentration Pathways |
| SAAL | South Australia Arid Lands |
| SDM | species distribution modelling |
| TGP | total grazing pressure |
| TM | Thematic Mapper |
| Western CMA | Western Catchment Management Authority |
| Western LLS | Western Local Land Service |

Glossary

| IN THIS REPORT | |
|-----------------------|---|
| TERM | DEFINITION |
| Hyporheic water flows | Below-surface flows |
| Short-range endemics | Species that occur only within a very small geographical area |
| Vicariant relicts | Species with ancestral characteristics that have become geographically isolated over time |

| IN ALL REPORTS IN THE SERIES | |
|--|--|
| TERM | DEFINITION |
| Adaptive capacity | The ability to change and therefore reduce gross vulnerability; includes issues such as mobility, financial resources and education |
| Bioregion | A large, geographically distinct area of land that has groups of ecosystems forming recognisable patterns within the landscape |
| C ₃ and C ₄ plants | The different methods plants use to convert carbon dioxide from air into organic compounds through the process of photosynthesis. All plants use C ₃ processes; some plants, such as buffel grass and many other warm climate grasses, also use C ₄ processes. C ₄ plants have an advantage in a warmer climate due to their higher CO ₂ assimilation rates at higher temperatures and higher photosynthetic optima than their C ₃ counterparts |
| Contentious species | A species that presents special challenges for determining the adaptation response to climate change, because it is both a threat and a beneficial species (Friedel et al. 2011, Grice et al. 2012) |

| IN ALL REPORTS IN THE SERIES | |
|---|--|
| TERM | DEFINITION |
| Dust Storm Index (DSI) | The Dust Storm Index is based on visibility records made by Bureau of Meteorology (BoM) observers. The DSI provides a measure of the frequency and intensity of wind erosion activity at continental scale. It is a composite measure of the contributions of local dust events, moderate dust storms and severe dust storms using weightings for each event type, based upon dust concentrations inferred from reduced visibility during each of these event types. |
| DustWatch | DustWatch is a community program that monitors and reports on the extent and severity of wind erosion across Australia and raises awareness of the effects of wind erosion on the landscape and the impacts of dust on the community. |
| Ecological refugia | Refugia defined according to the water requirements of the species they protect. The conservation significance of ecological refugia, and the priority assigned to their conservation, depends on the level of knowledge available for the species they support. |
| Evolutionary refugia | Those waterbodies that contain <i>short-range endemics</i> or <i>vicariant relicts</i> . Evolutionary refugia are most likely to persist into the future and should be accorded the highest priority in NRM adaptation planning. |
| Generalised Dissimilarity Modelling (GDM) | A method of modelling based on compositional turnover of a group of species at a location; it considers whole biological groups rather than individual species |
| Gross vulnerability of a system | The combination of exposure and sensitivity of system |
| Heatwave | Continuous period beyond a week when a particular threshold temperature is exceeded |
| Indicators of exposure | Factors such as days above a certain temperature, days without rainfall, population density |



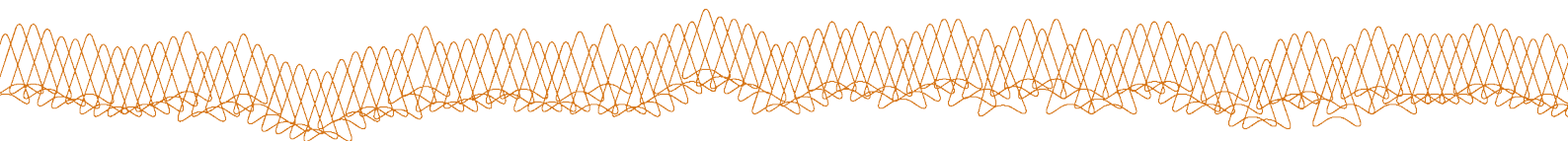
| IN ALL REPORTS IN THE SERIES | |
|--------------------------------------|---|
| TERM | DEFINITION |
| Indicators of sensitivity | How sensitive a system is to hazards; indicators include the types of dwellings people live in and the percentage of the population with certain health characteristics |
| ‘No regrets’ strategies | These strategies yield benefits even if there is not a change in climate |
| Novel ecosystem | Species occurring in combinations and relative abundances that have not occurred previously within a given biome (Hobbs et al. 2006) |
| Rainfall event | One or more closely spaced rainfalls that are large enough to produce a significant vegetation response |
| Refugia | Habitats that biota retreat to, persist in and potentially expand from under changing environmental conditions |
| Return period | The number of days from the end of one rainfall event to the start of the next |
| Reversible strategies | Flexible strategies that can be changed if predictions about climate change are incorrect |
| Safety margin strategies | Strategies that reduce vulnerability at little or no cost |
| Species Distribution Modelling (SDM) | A species-specific approach whereby observational records are used to model the current potential distribution of a species |
| Soft strategies | Strategies that involve the use of institutional, educational or financial tools to reduce species vulnerability to climatic change |
| Species invasiveness | A species that causes environmental or socioeconomic impacts, is non-native to an ecosystem or rapidly colonises and spreads (see Ricciardi and Cohen 2007). In the Invasive animals report it refers to non-native species (that is, those introduced to Australia post-1788) that have caused significant environmental or agricultural changes to the ecosystem or that are believed to present such a risk. |

| IN ALL REPORTS IN THE SERIES | |
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| TERM | DEFINITION |
| Strategies that reduce time horizons | Strategies that reduce the lifetime of particular investments |

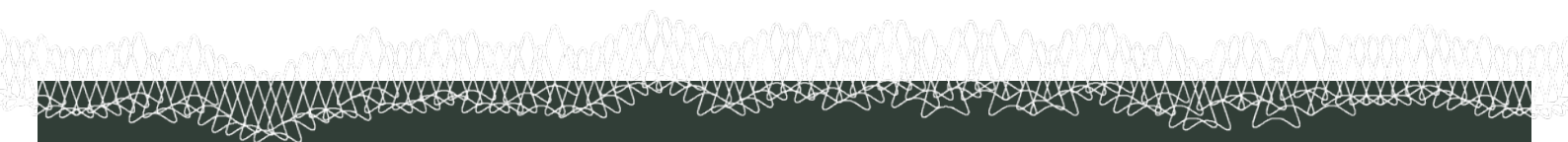
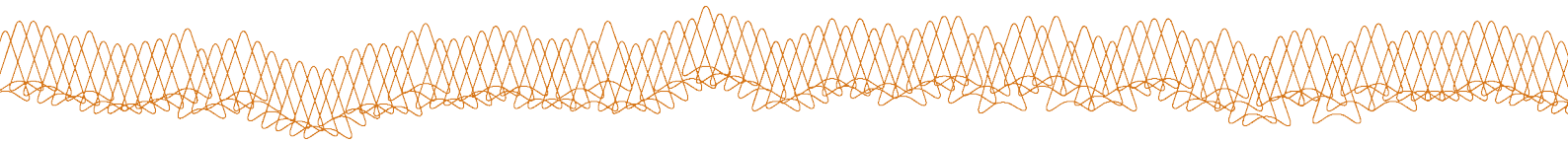


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