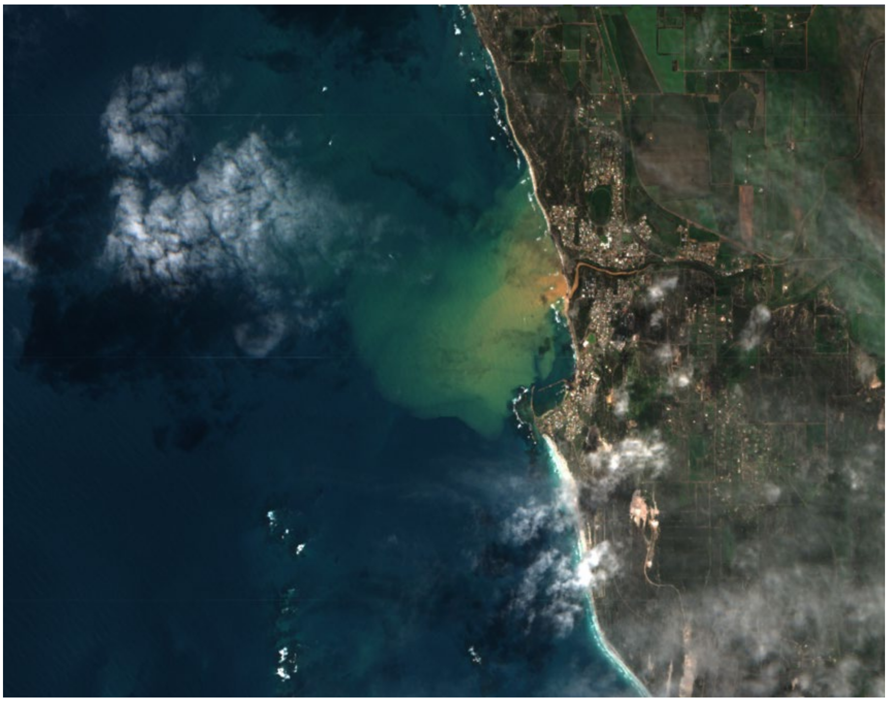
The influence of submarine groundwater discharge and freshwater flows on the ecology of the Western Rock Lobster



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Executive Summary

The influence of Submarine Groundwater Discharge (SGD) on coastal ecosystems of the West Coast Bioregion of Western Australia, and particularly its impact on the Western Rock Lobster (WRL) and the West Coast Rock Lobster Managed Fishery (WCRLMF), is poorly understood. This is despite that the region's unique oceanography and geological history, where the prevailing oceanography suppresses upwelling and there is limited nutrient input from the land, would predict that SGD could have a significant role in the productivity of coastal ecosystems. In addition, this region is reported to be drying and warming under the influence of climate change, and localised decreases in SGD have already been reported. Three linked objectives were originally proposed within this project:

1. Identify areas of significant submarine groundwater discharge (SGD) nearby established western rock lobster settlement monitoring sites.

2. Investigate the direct role of SGD on western rock lobster settlement rates.

3. Investigate the link between SGD and the extent and condition of important lobster habitat (e.g. seagrass).

To address the knowledge gaps surrounding SGD and inform further research, a workshop was convened in December 2020, bringing together experts from various disciplines. The workshop aimed to identify key research priorities and effective methodologies for studying SGD and its potential role in the productivity of coastal ecosystems.

The workshop discussions focused on key challenges including identifying knowledge gaps, recommending existing sources of data to inform data synthesis and future survey design, recommending viable methods for field surveys and an overall prioritisation of research questions. Participants and domain experts provided an evaluation of the strengths, weaknesses, and feasibility of the various approaches discussed. A key recommendation for future field surveys was to use a multi-sensor approach to detection and ground-truthing of SGD, due to the known constraints of detecting these flows in coastal waters. Of the top three research priorities identified by the workshop participants, the most fundamental was a focus on establishing the extent and any hotspots of SGD within a study area of interest. Understanding the knock-on impacts of changing land use, rainfall and climate on SGD was also deemed important.

From the workshop, one of the main recommendations for field survey methods was the remote sensing of sea surface temperature anomaly, as a large-scale indicator of SGD flows. However, after the workshop we conducted a study using this approach at key locations across the WCRLMF, where the monitoring of settlement, recruitment and catch of WRL is well established. This study of the seasonal and interannual variability in sea surface temperature anomalies found thermal remote sensing is unlikely to a useful indicator of SGD because of land heat contamination at the land-sea interface.

Another main recommendation for field work from the workshop, as a finer-scale indicator to identify SGD flows, was the use of radon gas detection in coastal systems. However, a pilot study demonstrated that although this method worked well to confirm SGD flows in surface river flows and at the shoreline, it was typically not sensitive enough to detect SGD at the sea surface in well mixed coastal environments and instead we recommended that future assessments with radon gas should focus on sampling directly from the seabed where SGD’s are suspected to emerge.

The outcomes of the workshop, along with the findings that sea surface temperature anomaly was unlikely to be a useful proxy to study SGD and that whilst Radon detection is a reliable sensor at the source of SGD it was typically not sensitive enough to detect SGD in typical well-mixed coastal environments, indicated that we did not have a sufficient level of knowledge on which to base our investigation of the original objectives. Therefore, the project pivoted to instead use the other recommendations of the expert workshop to design a future survey approach to better understand SGD processes within any area of interest across the West Coast Bioregion and to create a more informed understanding with which to plan for future studies. The recommended approach uses multi-disciplinary and multi-sensor sampling combined a spatially balanced survey design and was designed to be informed by data synthesis and expert knowledge, with adaptive approaches to identify and ground-truth any SGD hotspots. The proposed methodology would be adaptable to any location and form a first step to better understand the potential ecosystem role of these flows and provide a baseline for future work to understand how SGD influences the productivity of Western Australia's coastal ecosystems.

The influence of SGD on coastal ecosystems of the West Coast Bioregion are poorly understood. After the expert workshop, the project identified that the initial objectives proposed were not achievable and used the outputs of that workshop and pilot studies, to evaluate potential field methods, and recommend that future studies should instead focus on detailed characterisation of SGD within locations of interest. The proposed multi-sensor sampling approach and survey design provided here, would provide a robust basis for any future investigation of the role of SGD on WRL ecology and any implications for the WCRLMF.

Keywords

Submarine Groundwater Discharge, Western Rock Lobster, coastal productivity, fisheries ecology, local ecological knowledge, climate change

General Introduction

Recruitment to the Western Rock Lobster fishery has been recognised to be largely driven by environmental conditions (Caputi 2008; Kolbusz et al. 2022) but the role of freshwater and/or nutrients derived from submarine groundwater discharge from subterranean aquifers is unknown. Various anecdotal accounts from Western Australia, the Caribbean and New Zealand suggest that settlement hotspots for a range of rock lobster (Palinuridae) species are often associated with freshwater or groundwater discharge and water-borne chemical signals (Hinojosa et al. 2018) and freshwater discharge has been shown to be positively correlated with crab larval abundance (Boylan and Wenner 1993).

Submarine groundwater discharge (SGD) is defined as the flow of water from the coastal aquifer into the nearshore ocean via seabed sediments (Burnett and Dulaiova 2003), connecting freshwater reservoirs with the sea. The term SGD includes water from all salinities, whether it is freshwater from the coastal aquifer or seawater recirculated through the subterranean estuary (Moore 2010). These flows are recognised for transporting nutrients (Rodellas et al. 2015) and anthropogenic pollutants (Szymczycha et al. 2020) into the ocean, potentially driving biotic processes in coastal zones. SGD freshwater inputs may significantly shape species assemblages, with brackish water species dominating some assemblages in localised areas of high SGD flow rates in coastal ecosystems (Grzelak et al. 2018).

The role of SGD flows in coastal marine ecology varies depending on their salinity and nutrient composition. Input of nutrients via SGD may constitute a significant proportion of the total nutrient supply in a given area (Waska and Kim 2011; Andrisoa et al. 2019), with the positive effects of nutrients sourced from SGD demonstrated to extend through the trophic web, with evidence of increased abundance and body size of invertebrates in areas with SGD input (Stieglitz and Dujon 2017; Piló et al. 2018). In contrast, SGD may also contain chemicals such as land-derived pesticides may have detrimental effects on marine communities, including by reducing primary productivity and directly impacting marine species (Starke, Ekau, and Moosdorf 2020; Yu et al. 2022). Alternatively, localized reductions in salinity due to SGDs can be either beneficial or detrimental for marine communities, depending on the concentrations involved. For example, germination and seedling establishment of the seagrass *Zostera marina* has been found to be strongly influenced by salinity (Xu et al. 2016) with germination being more rapid in the presence of lower salinity SGD (up top 5 psu, Yue et al. 2019). On the other hand, very low and large-scale salinity intrusions have also been implicated in the fragmentation of seagrass meadows ultimately reducing their extent (Stipek et al. 2020). Equally though, flows can be bi-directional and seawater intrusion into coastal aquifers can occur when any reduction in groundwater flows or recharge, which can equally impact sensitive near-shore ecosystems that rely on the nutrients supplied by SGD (Johannes 1980).

In south-western Australia, the positive and negative effects of SGD in marine benthic communities remains largely unknown. However, earlier studies in Marmion Lagoon established that SGD can supply up to 50% of the nutrients required for the observed growth rates of macrophytes (Johannes and Hearnes 1985). In other comparable ecosystems, freshwater input has been observed to positively impact seagrass germination (Xu et al. 2016), and although no similar studies exist for temperate seagrass species in the southern hemisphere, SGD may have a role in the creation, maintenance and augmentation of seagrass beds.

In south-western Australia, SGD flow estimates from Geographe Bay, Cockburn Sound and Marmion Lagoon range from 240 - 4,800 m^3/day/km of coastline (Varma, Turner, and Underschultz 2010; Johannes and Hearnes 1985; Smith and Nield 2003). SGD in the mid-west of the state remains unknown, with anecdotal accounts of freshwater discharge within the centre of the Western Rock Lobster fishery at key historical recruitment and high catch hotspots of the Western Rock Lobster fishery, including: 7 Mile, Cliff Head and Freshwater Point. However, in the norther metropolitan region of Perth long-term monitoring of SGD at Quinns Rocks has documented how increased groundwater extraction, linked to rapid urbanisation, combined with reduced rainfall has led to unambiguous evidence of reduction in seaward SGD flows with are now replaced by seawater intrusion along the coastal margins (Costall et al. 2020). During the history of the Western Rock Lobster fishery there have been significant changes in land use adjacent to the fishery which has likely influenced the volume, salinity, and nutrient profile via SGD into the nearshore areas throughout the fishery (Bell et al. 1990). Western Rock Lobster fishers accounts from the 1960's recount that settlement and recruitment of Western Rock Lobster was greatest at river mouths, and that abundances of post-puerulus and juvenile lobster were much greater than are currently found throughout the fishery (J. Fitzhardinge, personal communication, March 20, 2020).

The direct influence of SGD on puerulus settlement rates is unknown but freshwater discharge has been shown to be positively correlated with crab larval abundance in certain regions (Boylan and Wenner 1993). Previous studies have demonstrated post-puerulus and early juvenile Western Rock Lobster exhibit a strong preference for the chemical signature of seagrass in aquaria (Brooker et al. 2022). These findings suggest that SGD may affect puerulus settlement rates either directly through chemotaxis or indirectly by impacting the extent and density of seagrass meadows. Hence, there is a need to investigate both the role of SGD and the presence of seagrass on puerulus settlement and subsequent recruitment rates into the fishery. The first field evidence to supporting the link between the presence of seagrass and recruitment rates of Western Rock Lobster comes from FRDC Project 2019-099 'Climate driven shifts in benthic habitat composition as a potential demographic bottleneck for Western Rock Lobster' which has documented a correlation between submerged aquatic vegetation extent, detected by satellite remote sensing, and juvenile lobster catch at coastal locations of the West Coast Bioregion typically dominated by seagrass (Figure 1).

In North America, some studies have recognised that land derived contaminants can potentially impact decapod settlement and survival, including heavy metals and endocrine disrupting chemicals, such as flame-retardants or pesticides targeting insects (McKenney 1999). Adult American Lobster (*Homarus americanus*) have been shown to be repelled by the presence of copper (McLeese 1975) and both flame-retardants (polybrominated diphenyl ethers - PBDEs) (Davies and Zou 2012) and various insecticides (Ghekiere et al. 2007) have been shown to disrupt moulting in marine crustacea. Alkylphenol pollution was implicated in a major die-off of American Lobster populations that occurred within Long Island Sound in 1999, with an acute impact on post-puerulus mortality during moulting (Laufer et al. 2013). However, initial broad screening studies conducted by the Western Australian ChemCenter found that a broad range of potential chemical contaminants were all below limits of detection within muscle and hepatopancreas tissue samples from Western Rock Lobster sampled adjacent to the metropolitan centre of Perth (Bornt et al. in prep). Given the lack of any detectable heavy metal and chemical contaminants found by Bornt et al. (in prep), the workshop and survey designed documented here did not include any objectives to study their presences in SGD.

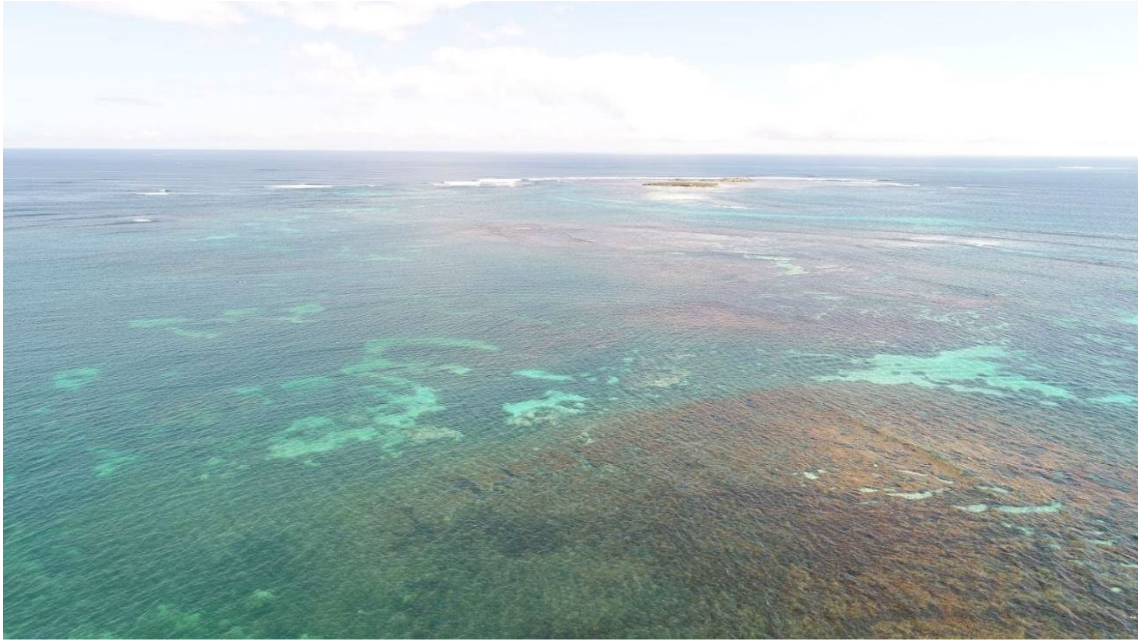

Figure 1 Mixed algal and seagrass assemblages at the Beagle Islands, WA.

Objectives

Previous research has established that early juvenile Western Rock Lobster have a strong preference for the chemical cues from seagrass assemblages, and in particular for *Amphibolis* spp (Brooker et al. 2022). There reports of an association between settlement by Western Rock Lobster and areas of increased terrestrial or SGD flows, but whether this is directly driven by response of the settling lobster to these flows, or the signal of associated increased productivity of benthic algae and seagrass assemblages is still an area for research. However, the nutrient budgets and both algal and seagrass productivity within the coastal lagoons along the mid-west and southwestern coasts are likely impacted by SGD flows (Johannes et al. 1994).

Globally there is only limited knowledge and understanding of the importance of SGD flows to coastal productivity but the mid-west and southwest of Australia provide an ideal location to study their impacts given the low levels of ocean productivity and very low nutrient inputs from the land (Johannes et al. 1994).

The overall objective of the project was to evaluate the role of submarine groundwater discharge (SGD) on the ecology of Western Rock Lobster and the extent and condition of important lobster habitat (e.g. seagrass). This information could then be used to understand how settlement and recruitment into the fishery, might be impacted by SGD. Three linked objectives were originally proposed within this project:

1. Identify areas of significant submarine groundwater discharge (SGD) nearby established western rock lobster settlement monitoring sites.

2. Investigate the direct role of SGD on western rock lobster settlement rates.

3. Investigate the link between SGD and the extent and condition of important lobster habitat (e.g. seagrass).

The first step to achieving these objectives was to hold an expert workshop convened to synthesis existing information and make recommendations for approaches to study the influence of submarine groundwater discharge (SGD) on the ecology of coastal ecosystems across the West Coast Bioregion of Western Australia.

From the workshop, one of the main recommendations for field survey methods was the remote sensing of sea surface temperature anomaly, as a large-scale indicator of SGD flows. This method has previously been used in the West Coast Bioregion (Varma, Turner, and Underschultz 2010) and internationally (Nandimandalam, Sharma, and Alagappan 2023) to detect SGD in coastal systems, but also in freshwater lake systems (Mallast et al. 2014). However, the current project found that at key locations across the WCRLMF, where the monitoring of settlement, recruitment and catch of WRL is well established, a study of the seasonal and interannual variability in sea surface temperature anomalies found thermal remote sensing is unlikely to a useful indicator of SGD because of land heat contamination at the land-sea interface.

Another main recommendation from the workshop was the use of radon gas detection in coastal systems to identify SGD flows. Similarly, this method has previously been used at various coastal locations internationally to detect SGD in coastal waters (Dulaiova et al. 2010; Nandimandalam, Sharma, and Alagappan 2023), where substantial SGD flows exist. However, a pilot study demonstrated that although this method worked well to confirm SGD flows in surface river flows and at known SGD emergences on the shore, it was not typically sensitive enough to detect SGD at the sea surface in well mixed near-shore coastal environments. Instead it was recommended that radon gas detection would only be useful once emergent low salinity flows had been identified, whereby suspected SGD flows could be tested for the presence of radon from water samples collected directly from the emergent source on the seabed. It is useful to note that many previous studies documenting SGD flows with either remote sensing of sea surface temperature anomaly or insitu radon gas detection, were in locations where the likely flows of SGD are typically 1-2 or more orders of magnitude greater that those predicted to occur along the West Coast Bioregion (Tularam and Krishna 2009), and in certain areas of the West Coast Bioregion, the substantial land-use change and groundwater pumping has already been documented to reverse the natural flows and instead salt water intrusion is occurring (Costall et al. 2020).

The outcomes of the workshop, along with the findings that sea surface temperature anomaly was unlikely to be a useful proxy to study SGD and that whereas radon gas detection is a reliable sensor to confirm the presence of SGD it was typically not sensitive enough to detect SGD in well-mixed coastal environments, indicated that we did not have a sufficient level of knowledge on which to base our investigation of the original objectives. Therefore, the project pivoted to instead design a survey approach to better understand and map SGD emergence within any nearshore area of interest across the West Coast Bioregion. The recommended survey proposed a multi-disciplinary and multi-sensor sampling approach combined a spatially balanced survey design, and was designed to be informed by data synthesis and expert knowledge, with adaptive approaches to identify and ground-truth any potential SGD hotspots. The proposed methodology would be adaptable to any location and be more likely to detect the potentially smaller magnitude SDG flows occurring across the West Coast Bioregion. We propose that this approach would form a first step to better understand the potential ecosystem role of SGD and provide a baseline for future work to understand how its flows may influence the productivity and ecology of the West Coast Bioregions coastal ecosystems.

The following chapters will first provide a summary of the expert workshop convened on the influence of submarine groundwater discharge (SGD) on the ecology of coastal ecosystems across the West Coast Bioregion of Western Australia. This workshop provided a series of recommendations for further desktop synthesis and field studies. In addition, we have provided supplementary information of the changing climate of the West Coast Bioregion of Western Australia and potential knock-on effects on groundwater flows, including predicted decreases over time in theses flows which then has important implications for our ability to study SGD and understand the ecological impact of SGD flows. We also provide a summary of the evaluation of remote sensing of sea surface temperature anomaly as an indicator of SGD. Finally, we will provide a recommended multi-disciplinary and multi-sensor survey design to be used in future studies to investigate the influence of SGD on the ecology of coastal ecosystems for areas of interest across the West Coast Bioregion of Western Australia, this includes pilot study information evaluating the use of radon gas to detect SGD. Importantly such a field survey approach would provide a robust basis for any future investigation and formulation of objectives of the role of SGD on WRL ecology and any implications for the WCRLMF.

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Workshop: The influence of submarine groundwater discharge (SGD) on the ecology

of coastal ecosystems across the West Coast Bioregion of Western Australia

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Workshop on the influence of submarine groundwater discharge on the ecology of coastal ecosystems across the West Coast Bioregion of Western Australia in Dec 2020 with 27 participants. Photograph by Tim Langlois.

Summary

The workshop was conducted on the 8th of December 2020 and had a total of 27 participants representing 8 organisations. The main objective of the workshop was to inform the study and investigation of the influence of submarine groundwater discharge (SGD) and freshwater flows on the ecology of coastal ecosystems across the West Coast Bioregion of Western Australia and

how these may influence Western Rock Lobster (WRL) ecology, settlement processes and recruitment into the West Coast Rock Lobster Managed Fishery (WCRLMF). The workshop used a ‘World Café’ approach to ask four main questions:

1. How do we identify specific areas of SGD across the WRL fishery?

2. How do we confirm the existence of SGD and quantify its flow at a local scale?

3. How do we characterise the composition of SGDs? What compounds are more important to test for? And

4. What are the major knowledge gaps of SGDs in marine systems?

The workshop produced a series of recommendations for both data synthesis and field studies, including listing the strengths and weakness of different approaches and ranking the likelihood of success and difficulty to employ those methods. In addition, a ranked list of priority questions for future studies was produced in a whole of workshop prioritisation exercise.

The workshop produced a set of detailed and broad recommendations to inform the future study and investigation into the influence of submarine groundwater discharge (SGD) and freshwater flows on the ecology of coastal ecosystems across the West Coast Bioregion and how these influence WRL ecology, settlement processes and recruitment into the WCRLMF. The recommendations will be particularly useful to inform the design of any future synthesis and field studies of SGD across the West Coast Bioregion of Western Australia.

Introduction

The scientific understanding of the influence of submarine groundwater discharge (SGD) on coastal ecosystems of West Coast Bioregion of Western Australia is limited. We do know that SGD flows have the potential to deliver large volumes of low salinity and nutrient rich waters to coastal areas and lagoons and suspect that changes in these flows will impact the species-specific growth of seagrass and macroalgal assemblages and potentially the animals associated with these habitats such as Western Rock Lobster.

The unique oceanography of mid-western and southwestern Australia, with the dominance of the Leeuwin Current supressing upwelling along the coast (Mills et al. 1996) also results in decreased mixing between offshore and nearshore coastal waters (Mills et al. 1996), making productivity within these coastal waters even more reliant on nutrient inputs from terrestrial surface or subterranean flows.

Recent research has established that early juvenile Western Rock Lobster have a strong preference for the chemical cues from seagrass assemblages, and in particular for *Amphibolis* spp (Brooker et al. 2022). There is evidence of a linkage between settlement by Western Rock Lobster and areas of increased terrestrial or SGD flows, but whether this is directly driven by response of the settling lobster to these flows, or the signal of associated increased productivity of benthic algae and seagrass assemblages is still an area for research. However, the nutrient budgets and both algal and seagrass productivity within the coastal lagoons along the mid-west and southwestern coasts are likely highly impacts by SGD flows (Johannes 1980). The overall objectives of the workshop were to bring together information and suggest study methods on how SGD may influence the ecology of Western Rock Lobster (WRL), its settlement processes and recruitment into the West Coast Rock Lobster Managed Fishery (WCRLMF).

Globally there is a lack of knowledge and understanding of the importance of SGD flows to coastal productivity but the mid-west and southwest of Australia provide an ideal location to study their impacts given the low river and estuary surface flows.

The West Coast Bioregion of Western Australia, characterised by its unique oceanography and diverse marine life, presents a potentially useful case study for understanding SGD's ecological impacts, given the documented climate-driven hydrological changes in the region (Priestley et al. 2023; Costall et al. 2020).

To address this knowledge gap, an expert group workshop was convened on December 8th, 2020. This workshop, employing a "World Café" and group prioritisation approach, sought to define key research priorities and identify effective methodologies for studying SGD in this region.

Workshop Context and Objectives

The workshop brought together 27 participants representing 8 organisations, including WRL fishers and researchers, fostering a multi-disciplinary approach to tackle the complexities in studies of SGD.

Central to the workshop were five key challenges (Figure 2):

- Identify the major knowledge gaps in SGD understanding
- How can we pinpoint specific SGD areas within the Western Rock Lobster fishery?
- How can we confirm and quantify SGD flow at a local scale?
- What is the composition of SGDs, and which compounds warrant further testing?
- What are the major knowledge gaps concerning SGDs in marine systems?

Planned Workshop Outcomes

- The workshop was designed to elicit a series of recommendations for both synthesis activities of existing information and field studies to inform our understanding of SGD across the West Coast Bioregion of Western Australia and how SGD may influence the ecology of WRL, its settlement processes and recruitment into the WCRLMF.
- Participants were asked to evaluate each recommendation, considering their strengths, weaknesses, potential success rates, and ease of implementation.
- A collaborative prioritisation exercise further identified critical research questions for future investigation.

Workshop approach

The first half of the workshop used a 'World cafe' approach where attendees were divided into groups to address one of the five key challenges and using the supporting questions (Figure 2). Each group then presented back to the workshop, their own list of priority research questions and complimentary data synthesis and field data collection recommendations. The whole of workshop then organised the recommendations into either recommended synthesis studies or field study approaches, with group of domain experts providing a scoring of the likelihood of success and difficulty for each of the proposed approaches.

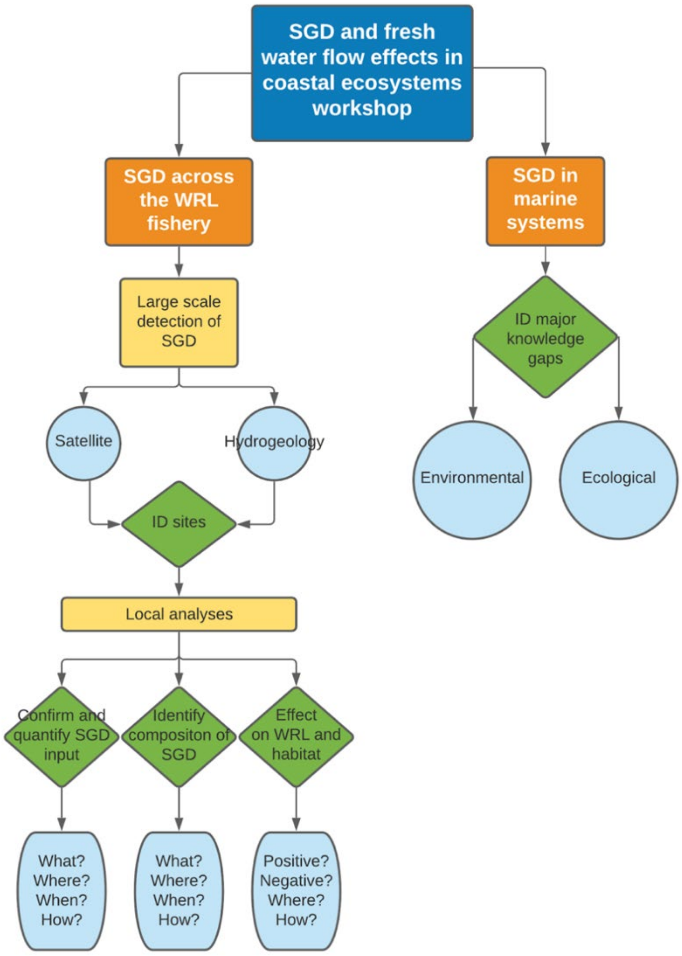
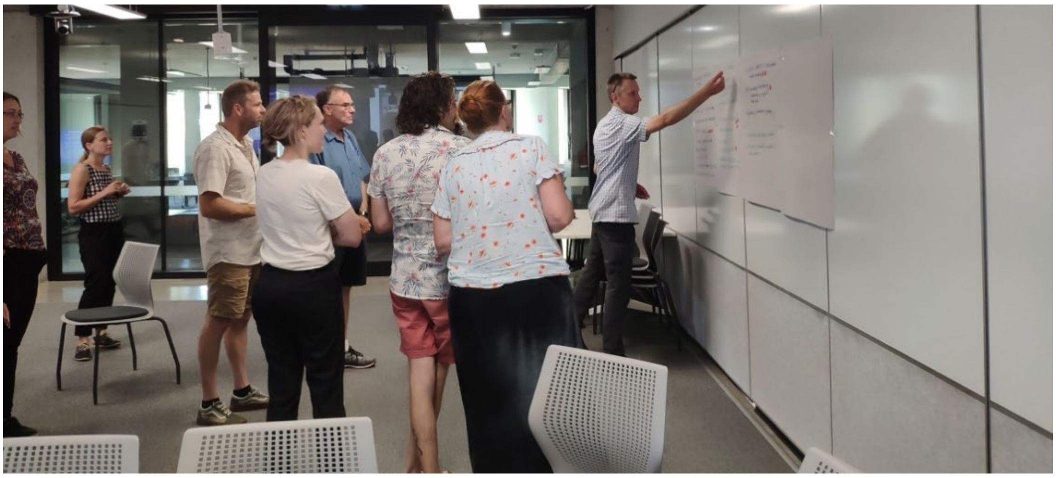


Figure 2 Conceptual diagram of workshop structure. The green rhombi describe the five challenges to be addressed, and the blue shapes list the specific questions.

a)



b)

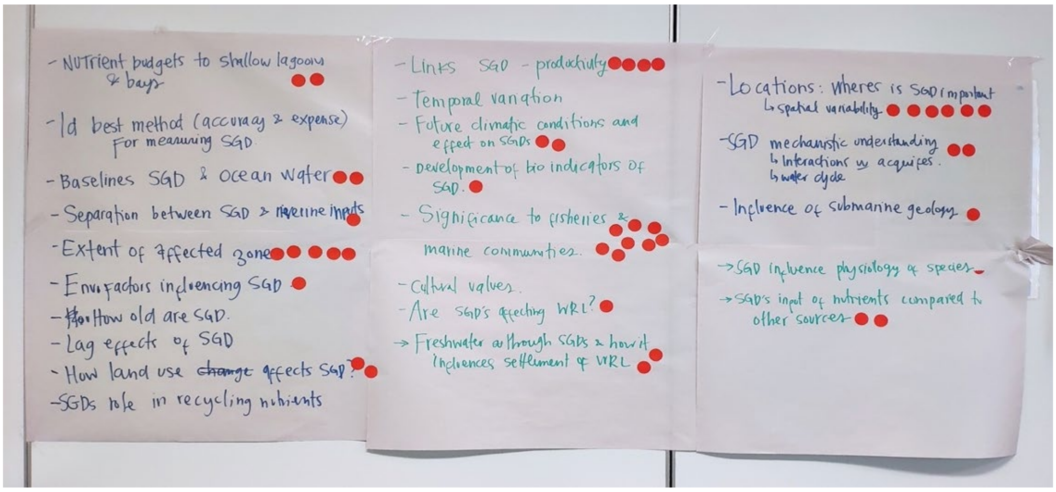


Figure 3 Workshop a) prioritization activity of b) questions to inform the study the influence of submarine groundwater discharge (SGD) on the ecology of coastal ecosystems across the West Coast Bioregion of Western Australia. Photographs Tim Langlois.

The second half of the workshop involved a group prioritisation process, using the priority research questions generated in the first half of the workshop (Figure 3) to inform the study of the influence of submarine groundwater discharge (SGD) and freshwater flows on the ecology of coastal ecosystems across the West Coast Bioregion of Western Australia and how SGD may influence the ecology of WRL, its settlement processes and recruitment into the WCRLMF. This process involved every group member having three votes and allocating those votes to the research questions they perceived had the highest priority.

Workshop outcomes

World Café – Synthesis study recommendations

Table 1 outlines various sources of information suggested by the workshop participants to inform synthesis to inform the study of Submarine Groundwater Discharge (SGD) and freshwater flows on coastal ecosystems in Western Australia's West Coast Bioregion and how SGD may influence the ecology of WRL, its settlement processes and recruitment into the

WCRLMF. All participants were asked to provide a scoring of the likelihood of success and difficulty for each of the proposed approaches.

Data synthesis methods proposed:

- WIR (Water Information Reporting System): This open-access government database provides extensive time-series data on stream and groundwater flows and their chemistry. Although data is readily available it lacks complete time series and is mostly limited to metropolitan areas.
- Regional Groundwater Model: This model offers extensive spatial coverage and calculates SGD discharge into coastal waters. Its strength lies in its broad scope, but its coarse resolution might not capture finer-scale variations in SGD flows likely to be relevant for local studies on the influence of SGD on marine ecosystems.

Bathymetry and Elevation Models: This open-access data can correlate known SGD points with topographic relief to predict other potential SGD emergence points. However, its usefulness depends on a consistent relationship between SGD and topography and so could be a useful proxy when combined with other sources of information. The potential correlation between submerged paleo-channels and SGD was noted.

- Hydrological and Geological Reports: These reports from government and industry provide valuable information on aquifers and groundwater-bearing geology. However, their accessibility and consistency can be limited, and some are private as typically generated by private developments and resource projects.
- Local Expert Knowledge (LEK): Interviews with local fishers and experts can help identify likely areas of SGD at a large scale and validate remote sensing studies.

Overall, the workshop recommendations for synthesis studies (Table 1) highlights a range of approaches with varying strengths and weaknesses for studying SGD. The most suitable methods will depend on specific research questions, available resources, and the spatial scale of the study.

Based on the workshop participants combined scoring for likelihood of success and difficulty, the top three recommendations to inform research on SGD included synthesising existing information from Western Australia’s Water Information Reporting system, with bathymetry and elevation information in consultation with local expert knowledge

Table 1 Workshop recommendations for synthesis studies and methods to study the influence of submarine groundwater discharge (SGD) and freshwater flows on the ecology of coastal ecosystems across the West Coast Bioregion of Western Australia. Ranking was created by combining domain expert score for likelihood of success (1 likely – 5 unlikely) and difficulty (1 easy - 5 hard) for each synthesis method.

Synthesis method	Description	Strengths / Weakness	Likelihood * Difficulty = Ranking	Recommendations
WIR (water information reporting system) wir.water.wa.gov.au	Time series data – of stream and groundwater flows and chemistry.	*Strength* – Open-access and extensive spatial dataset. *Weakness* – incomplete time series at some key locations. Mostly limited to metropolitan regions.	3 * 1 = 3	Could be used in combination with other existing data sources to inform SGD field survey design. Could be used in combination with isotope and trace element field surveys to identify SGD sources.
Regional ground water model	Extent of Moore River to Augusta. Calculating the SGD discharge to coastal waters.	*Strength* – Extensive spatial converge. *Weakness* – Relatively coarse resolution that is not able to resolve variation in SGD flows at less than 100 km.	3 * 3 = 6	Could be used in combination with other existing data sources to inform SGD field survey design. Could be used in combination with isotope and trace element field surveys to identify SGD sources.
Bathymetry and elevation models	Bathymetry and elevation data could be used to predict SGD emergence points.	*Strength* – Open-access and could be used to correlate known SGD emergence points with topographic relief to infer other emergence points.	3 * 1 = 3	Could be used in combination with other existing data sources to inform SGD field survey design.

		Weakness – Only useful if SDG emergence points are consistently correlated with topographic relief.		Paleochannels have been found to be associated with SGD exchange (Mulligan, Evans, and Lizarralde 2007)
Hydrological and geological reports	Both government and industry reports that will include maps of aquifers and ground water bearing geology.	*Strength* – Some open-access and could be used infer emergence points. *Weakness* – Majority are private and can lack consistency between reporting standards and accessibility of data.	3 * 3 = 6	Could be used in combination with other existing data sources to inform SGD field survey design.
Local Expert Knowledge (LEK)	Structured interviews with commercial fishers or other local experts	*Strength* – can be used to identify likely areas of current SGD at large scale and to ground truth RS studies. *Weakness* – could be limited by availability of LEK.	2 * 2 = 4	Could be used in combination with other existing data sources to inform SGD field survey design.
TEK (Traditional Ecological Knowledge)	Collaboration with indigenous knowledge holders	*Strength* – can be used to identify likely areas of current SGD at large scale and to ground truth RS studies. *Weakness* – would need substantial time to develop collaboration and could be limited by availability of TEK.	Not ranked	Would need substantial time to develop collaboration process. Including following AIATISIS code to develop any collaboration through FPIC, ICIP and shared objectives.

World Café – Field study recommendations

Table 2 outlines various field techniques proposed to investigate the influence of SGD on coastal ecosystems in Western Australia. It evaluates the strengths and weaknesses of each method, along with their likelihood of success and difficulty of implementation, offering recommendations for practical application.

Key Methods & Recommendations:

Radon Surveys (Point Sample): This method, involving discrete radon gas measurements, is recognised for its accuracy and suitability for both land and vessel-based studies. It is cost-effective in terms of replication, making it useful for intensive spatio-temporal monitoring. However, limitations include radon's rapid dissipation in coastal environments and the initial high equipment cost. It is suggested that radon sampling be integrated with other ground-truthing methods.

Radon Surveys (Transect): Continuous radon measurement along a transect offers a spatial perspective on SGD emergence. However, the challenges of rapid radon dissipation and high costs persist, including limitations of the limit of detection given the rapid rate at which radon can dissipate in coastal waters. Recommendations include combining this method with other ground-truthing methods and employing an adaptive survey design for targeted sampling.

- Radium Isotopes & Strontium Traces: Both methods are supported for their accuracy in estimating SGD emergence time and flow rates compared to radon. Radium isotopes can further identify aquifer sources, while strontium traces can also identify historical SGD areas. The major drawback for both these approaches lies in the high cost per sample analysis, making them more suitable for detailed studies after initial SGD source identification.
- Remote Sensing of Sea Surface Temperature Anomaly: Measuring sea surface temperature anomalies can potentially reveal SGD areas due to temperature differences. However, this method can be challenging in regions with complex oceanographic regimes. The recommendation emphasizes strategic timing, focusing on cool patches during warm seasons (February and March), ideally in targeting low-wind and therefore low surface mixing conditions.
- Remote Sensing of Submerged Aquatic Vegetation (SAV): The location and species composition of SAV can indirectly indicate SGD presence. While accessible through public satellite imagery, distinguishing between seagrass and macroalgae necessitates in-situ sampling. The consideration of higher-resolution but costlier Worldview imagery is also recommended.
- Remote Sensing of Chlorophyll: Remote sensing of chlorophyll can suggest nutrient influence from SGD, but it is thought to be a weak and indirect indicator. Complementary in-situ sampling is necessary to validate SGD presence. Again, higher-resolution Worldview imagery might be beneficial, albeit with associated costs.
- Oceanographic Instruments Sampling: Transect or point count sampling with Conductivity, Temperature, and Density instruments are deemed cost-effective for identifying current SGD areas at a large scale, especially when deployed from ROVs or vessels. This method could integrate well with spatial and adaptive sampling programs.
- Oceanographic Instruments Sampling: Nutrient and Chlorophyll: Fluorometer sampling can infer localized nutrient impacts from SGD. While useful for ground-truthing remote sensing data, phytoplankton blooms can be caused by other factors, making this a less reliable SGD indicator. Combining this with other methods and adaptive sampling is could be beneficial as part of a multi-sensor array.

The workshop recommendations for field sampling methods highlight the potential of a multi-sensor, and potentially, staged approach to studying SGD, given the strengths and limitations of individual methods raised by the workshop participants (Table 2). The ideal approach would likely involve a combination of these techniques, tailored to specific study location and resource constraints. To gain a comprehensive understanding of SGD's influence on the West Coast Bioregion's coastal ecosystems, the importance of strategic survey design and adaptive sampling to first estimate the extent and any hotspots of SDG was also emphasised by the workshop participants.

Based on combined scoring for likelihood of success and difficulty, workshop participants recommended a multi-pronged approach to study SGD, combining physical measurements (i.e. CTD) and biological indicators (e.g. fluorometer) from oceanographic instruments, along with radon surveys for confirmation (Table 2)

Table 2 Workshop recommendations for field studies and methods to study the influence of submarine groundwater discharge (SGD) and freshwater flows on the ecology of coastal ecosystems across the West Coast Bioregion of Western Australia. Ranking was created by combining domain expert score for likelihood of success (1 likely – 5 unlikely) and difficulty (1 easy - 5 hard) for each synthesis method.

Field method	Description	Strengths / Weakness	Likelihood * Difficulty = Ranking	Recommendations
Radon survey – point sample	Discrete measurement of dissolved radon gas. Concentration of radon provides a proxy for time that SGD has been subterranean	*Strengths* - Point samples can provide more robust estimates of radon content including replication across area of interest. Can be used on vessel or for land-based studies to provide immediate information on the presence and relative concentration of SGD. Cost of replication is relatively low so well suited to intensive temporal and spatial monitoring. *Weakness* - Radon can rapidly dissipate when SGD emerges and so may be insensitive. Can vary seasonal variation in SGD with flow High initial cost of instrumentation, consumables and servicing ($15k + annual cost of ~$3k).	3 * 1 = 3	Radon water sampling could be combined with other ground truthing activities.
Radon survey – transect	Continuous measurement of dissolved radon gas along a transect.	*Strengths* – Continuous samples (e.g. from boat-based surveys) can be used to ground truth large areas. *Weakness* - Radon can rapidly dissipate when SGD emerges and so may be highly insensitive in coastal environment due to rapid mixing.	2 * 2 = 4	Radon water sampling could be combined with other ground truthing activities. Could be used in an adaptative survey design to first identify and then

	Patterns in spatial concentration of radon provides a proxy for areas of SGD emergence and for time that SGD has been subterranean.	High initial cost of instrumentation, consumables and servicing ($15k + annual cost of ~$3k).		corroborate the detection of radon using a combination of continuous transect and discrete point sampling approaches.
Radium isotopes	Measurement of ratio of four radium isotopes	*Strength* - provide more accurate measure of time since emergence for SGD than radon (i.e. estimate of half-life degradation since emergence) and can be used to infer flow rates. Ratio of four radium isotopes can also be used to identify aquifer source in areas of low groundwater mixing. *Weakness* – High cost of analysis per sample (~$200).	3 * 3 = 9	Likely to be only beneficial for detailed studies once the locations of SGD sources are established.
Strontium traces	Measurement of strontium	*Strength* - provide more accurate measure of time since emergence than radon and can be used to infer flow rates. *Weakness* – High cost of analysis per sample (~$300)	3 * 3 = 9	Likely to be only beneficial for detailed studies once the locations of SGD sources are established.
Remote sensing - temperature	Measurement of sea surface temperature anomaly. Areas of SGD emergence should appear cooler in warm season and warmer in cool season	*Strength* – can be used to identify likely areas of current and historical SGD at large scale. *Weakness* – due to oceanographic regime along west coast, including the influence of Leeuwin Current and Capes current, difficult to distinguish any temperature signal from SGD from coastal currents and mixing and surface run-off.	3 * 2 = 6	Likely that searching for cool patches during warm sea surface periods offers best opportunity on the west coast, February and March likely provides optimal time to search for cool patches along coast indicating SGD, ideally during periods of low wind.

Remote sensing – submerged aquatic vegetation (SAV)	Location, extent and species composition of SAV could indicate the presence of SGD	*Strength* – can be used to identify likely areas of current and historical SGD at large scale. Suitable RS imagery (i.e. LandSat 8) can be publicly accessed. Weakness – remote sensing of SAV cannot readily distinguish between seagrass and macroalgae assemblages of species and so would need to be complemented by insitu sampling of SAV, using drop cameras and in water sampling and for evidence of SGD.	3 * 2 = 6	Different salinities and nutrients provided by SGD have been reported to favour the establishment and growth of different seagrass and algal species. Any RS studies would need to be complemented by in-water sampling to identify different seagrass and algal species, and sample SGD flows likely with divers or ROV. Consider availability of Worldview imagery that is higher resolution but has associated cost (i.e. ~$2,000 per 10 km^2)
Remote sensing – chlorophyl	Location and extent of coastal chlorophyl could indicate the presence of SGD and impact of associated nutrients	*Strength* – can be used to identify likely areas of current and historical SGD at large scale. Suitable RS imagery (i.e. LandSat 8) can be publicly accessed. *Weakness* – remote sensing of chlorophyl may only be a weak and indirect indicator of nutrients associated with SGD.	4 * 2 = 8	Different nutrients provided by SGD have been reported to correlate with localised blooms of phytoplankton species. Any RS studies would need to be complemented by insitu sampling to identify and sample SGD flows, likely with divers. Consider availability of Worldview imagery that is higher resolution but has associated cost (i.e. ~$2,000 per 10 km^2)
Oceanographic instrument - transect	Transects with Conductivity Temperature and Density (CTD)	*Strength* – can be used to identify likely areas of current SGD at large scale. ROV or vessel deployed CTD transects provide the most cost-effective solution.	3 *	ROV and vessel deployed CTD transects provide the most cost-effective solution and could be used

	instrumentation deployed from vessel, sail drone, glider, Remotely Operated Vehicle (ROV) or Autonomous Underwater Vehicle (AUV)	*Weakness* – sail drone or glider will provide the most cost-effective option but not practical in nearshore situation, AUV expensive and not practical in near shore situation.	1 = 3	effectively in an adaptive sampling program to localise SGD locations
Nutrient and chlorophyl transects	Transects with fluorometer from vessel to infer localised impact of nutrients from SGD	*Strength* – can be used to identify likely areas of current SGD at large scale and to ground truth RS studies. *Weakness* – Spatial occurrence of phytoplankton blooms maybe due to other localised processes and not a good indicator of SGD.	3 * 2 = 6	ROV or vessel deployed fluorometer transects could be cost-effectively combined with other methods and used as part of an adaptive sampling program to localise SGD locations

Whole of workshop research question prioritisation outcomes

A final part of the workshop involved the voting for priority research questions, regarding the influence of SGD and freshwater flows on coastal ecosystems in Western Australia's West Coast Bioregion. These research questions were identified from the first half of the workshop (Table 3).

Highest priorities

The most pressing questions focused on the **ecological significance of SGD**, including its effects on fisheries and marine communities. However, the greatest priority was identified to be the identification of extent and hotspots within a study location. Understanding the **spatial variability and extent of SGD-influenced areas** was found to be the highest priority, to then inform future studies of the **ecological significance of SGD**.

Secondary Concerns

Questions related to the **mechanisms and drivers of SGD** were ranked lower but still considered important. These included understanding the baseline composition of SGD compared to ocean water, the link between SGD and primary/secondary productivity, the influence of land use and future climate on SGD, and the role of SGD in nutrient budgets and recycling.

Least Priority

Questions on specific methodological approaches, such as cost-effective study techniques and the ability to separate SGD from surface water flows, received the lowest priority. Similarly, inquiries about the age of SGD, lag effects, and temporal variations were not prioritized in this workshop with emphasis instead being given to mapping the existence, extent and any hotspots of SGD within a study location.

Table 3 Workshop prioritisation of questions to inform the study the influence of submarine groundwater discharge (SGD) and freshwater flows on the ecology of coastal ecosystems across the West Coast Bioregion of Western Australia.

Priority questions	Votes
What is the significance of SGD effects to fisheries and marine assemblages	8
What is the spatial variability of SGD; identify hotspots where SGD is important?	6
What is the extent of areas affected by SGD?	5
What baselines of compounds (e.g. nutrients) are in SGD versus ocean water?	4
What are the links between SGDs and both primary and secondary productivity?	4
Do freshwater inputs through SGD and affect settlement of WRL?	2
How does land use affects SGDs?	2
What is the effect of future climatic conditions on SGDs?	2
What role do SGD have in the nutrient budgets of shallow lagoons and bays?	2

We need to improve the mechanistic understanding of SGDs: are SGD simply an interaction of aquifers and the water cycle?	2
What is the influence of submarine geology on SGDs?	1
Does local but consistent exposure to SGD influence species (e.g. seagrass or algae) physiology?	1
What bioindicators can be developed for SGDs?	1
Do we need to refine how SGD vs. surface water flows can be separated using their chemical and compound signatures?	1
How can we determine environmental factors that influence SGD?	1
What are the most accurate and cost-effective approaches to study SGD?	0
How can we age SGDs?	0
How can we study the lags effects in the flows of SGDs?	0
What is the role of SGDs role in nutrient recycling?	0
How we study temporal variation in SGD?	0
What are the cultural values of SGD?	*

*Cultural values of SGD were not voted due to lack of representation of Aboriginal people in the workshop.

Workshop Summary

Addressing Knowledge Gaps

We have a limited understanding of how submarine groundwater discharge (SGD) influences the coastal ecosystems of Western Australia's West Coast Bioregion compared to other regions around the globe (Grzelak et al. 2018; Varma, Turner, and Underschultz 2010). However, it is recognised that SGD, by delivering low-salinity and nutrient-rich water, is likely to significantly impact marine ecosystems (Johannes 1980). The unique oceanographic conditions of the West Coast Bioregion, with limited upwelling and mixing (Mills et al. 1996), further emphasise the potential importance of SGD as a nutrient source for coastal productivity.

Workshop Objectives

To address this knowledge gap, our workshop brought together experts from diverse fields to bring together existing information and suggests approaches to better understand how SGD may influence the ecology of WRL, its settlement processes and recruitment into the WCRLMF. The primary objectives included identify key research priorities to inform the above, and the workshop produced a series of recommendations for data synthesis which could then be used to design cost-effective field sampling.

Key Findings and Recommendations

The workshop highlighted the need for a multi-faceted approach to SGD research, partly necessitated by the lack of existing benchmark information or understanding of the role of SGD in the coastal ecosystems of the West Coast Bioregion but also necessary due to recognised difficulties in identifying SGD in coastal environments.

Data Synthesis

- Recommendations included utilising existing data sources such as the Water Information Reporting System (WIR), regional groundwater models, bathymetry and elevation models, and hydrological and geological reports.
- These were ranked by combining domain expert score for likelihood of success and difficulty for each synthesis method (Table 4).
- The importance of incorporating local expert knowledge was also emphasised.

Table 4 Recommended ranking for synthesis studies and methods to study the influence of submarine groundwater discharge (SGD) and freshwater flows on the ecology of coastal ecosystems across the West Coast Bioregion of Western Australia. Ranking was created by domain experts (see Table 1).

Synthesis method	Rank
WIR (water information reporting system)	3
Bathymetry and elevation models	3
Local Expert Knowledge (LEK)	4
Regional ground water model	6
Hydrological and geological reports	6

Field studies

- A variety of field methods were proposed, including remote sensing techniques, and oceanographic instrument sampling, complemented by radon ground-truthing.
- The strengths and weaknesses of each method were assessed and were ranked by combining domain expert score for likelihood of success and difficulty for each synthesis method (Table 5).
- The use of a multi-sensor approach and spatially-adaptive sampling strategies was recommended to maximise efficiency and address the challenges posed by the difficulty of detecting SGD.

Table 5 Recommended ranking for field studies and methods to study the influence of submarine groundwater discharge (SGD) and freshwater flows on the ecology of coastal ecosystems across the West Coast Bioregion of Western Australia.

Field method	Rank
Radon survey – point sample	3
Oceanographic instrument - transect	3
Radon survey – transect	4
Remote sensing - temperature	6
Remote sensing – submerged aquatic vegetation	6
Nutrient and chlorophyl transects	6
Remote sensing – chlorophyl	8
Radium isotopes	9
Strontium traces	9

Priority Research Questions

- The workshop identified the identification of the extent and hotspots of SGD as the top research priority (Table 3).
- Understanding the ecological significance of SGD, including its effects on fisheries and marine communities, was also considered crucial.
- Questions related to the mechanisms and drivers of SGD, such as its composition, the influence of land use and climate change, and its role in nutrient budgets, were also prioritised, although to a lesser extent.

Conclusion

To meet the overall objective of understanding how SGD may influence the ecology of WRL, its settlement processes and recruitment into the WCRLMF, the subsequent chapters evaluate two of the proposed field methods and then proposes a multi-disciplinary and multi-sensor survey of submarine groundwater discharge at key locations of interest within the West Coast Bioregion of Western Australia. Firstly, an evaluation of sea surface temperature anomaly from remote sensing imagery, as a large-scale indicator of SGD flows, is evaluated. Then the use of radon gas for the detection of SGD at finer-scales is evaluated, as a pilot study within the proposed survey design to characterise SGD within a region of interest. Using the top synthesis recommendations (Table 4) to inform a spatially-adaptive multi-sensor field survey designed around the field method recommendations (Table 5). Mapping the extent and hotspots of SGD, will be the first step to improving our understanding of its ecological impacts, using the top synthesis recommendations (Table 4) to inform a spatially-adaptive multi-sensor field survey designed around the field method recommendations (Table 5). This understanding is particularly crucial given the documented changes in regional hydrology (see Supplementary Information 1 'The changing climate of the West Coast Bioregion of Western Australia and potential influence on groundwater flows'), such as decreased winter rainfall and increased temperatures, which are likely impacting SGD flows and coastal ecosystems (see Costall et al. 2020).

Acknowledgements

We thank all the workshop participants (see Supplementary Table 1) and in particular Belinda Martin and Katrina Bornt for assistance in running the workshop. We also extend thanks to John Fitzhardinge for his input during the initial stages of planning. This research was conducted as part of the UWA Marine Ecology Group, under UWA Human Ethics Protocol 2019/RA/4/20/4296 and was funded by the Fisheries Research and Development Corporation (Project Number 2019-101).

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Supplementary Materials

Supplementary Table 1. List of workshop participants, domain of expertise and affiliation.

Name	Expertise	Affiliation
Luke Twomey	Biological Oceanography	West Australian Marine Science Institute
Andrew Jeffs	Crustacean biology	University of Auckland
Pauline Grierson	Biogeochemist	The University of Western Australia
Greg Skrzypek	Biogeochemist	The University of Western Australia
Jen Middleton	Biogeochemistry	The University of Western Australia
Jess Kolbusz	Biological Oceanography	The University of Western Australia
Julian Partridge	Fish biologist	The University of Western Australia
Aleksey Sadekov	Geochemistry	The University of Western Australia
Don McFarlane	Hydrologist	The University of Western Australia
Matt Hipsey	Hydrologist	The University of Western Australia
Katrina Bornt	Marine ecology	The University of Western Australia
Tim Langlois	Marine ecology	The University of Western Australia
Chari Pattiaratchi	Oceanography	The University of Western Australia
Belinda Martin	Seagrass	The University of Western Australia
Marion Cambridge	Seagrass, macroalgae	The University of Western Australia
Gary Kendrick	Seagrass, macroalgae	The University of Western Australia
Matt Fraser	Seagrass, microbial chemistry	The University of Western Australia
Renae Hovey	Seagrass, remote sensing	The University of Western Australia
Sharyn Hickey	Seagrass, remote sensing	The University of Western Australia
John Fitzhardinge	Retired fisher	Southerly Designs

Kathryn McMahon	Seagrass, macroalgae	Edith Cowan University
Pere Masque	Submarine groundwater discharge	Edith Cowan University
Kieryn Kilminster	Seagrass, biogeochemist	Department of Water and Environmental Regulation
Frances D'Souza	Water quality	Department of Water and Environmental Regulation
Ben Radford	Survey design, spatial ecology	Australian Institute of Marine Science
Simon de Lestang	Crustacean biology	Aquatic Science and Assessment - Department of Primary Industries and Regional Development
Jason How	Crustacean biology	Aquatic Science and Assessment - Department of Primary Industries and Regional Development

Evaluation of Field Methods: Remote sensing of sea surface temperature anomaly, as a large-scale indicator of SGD flows

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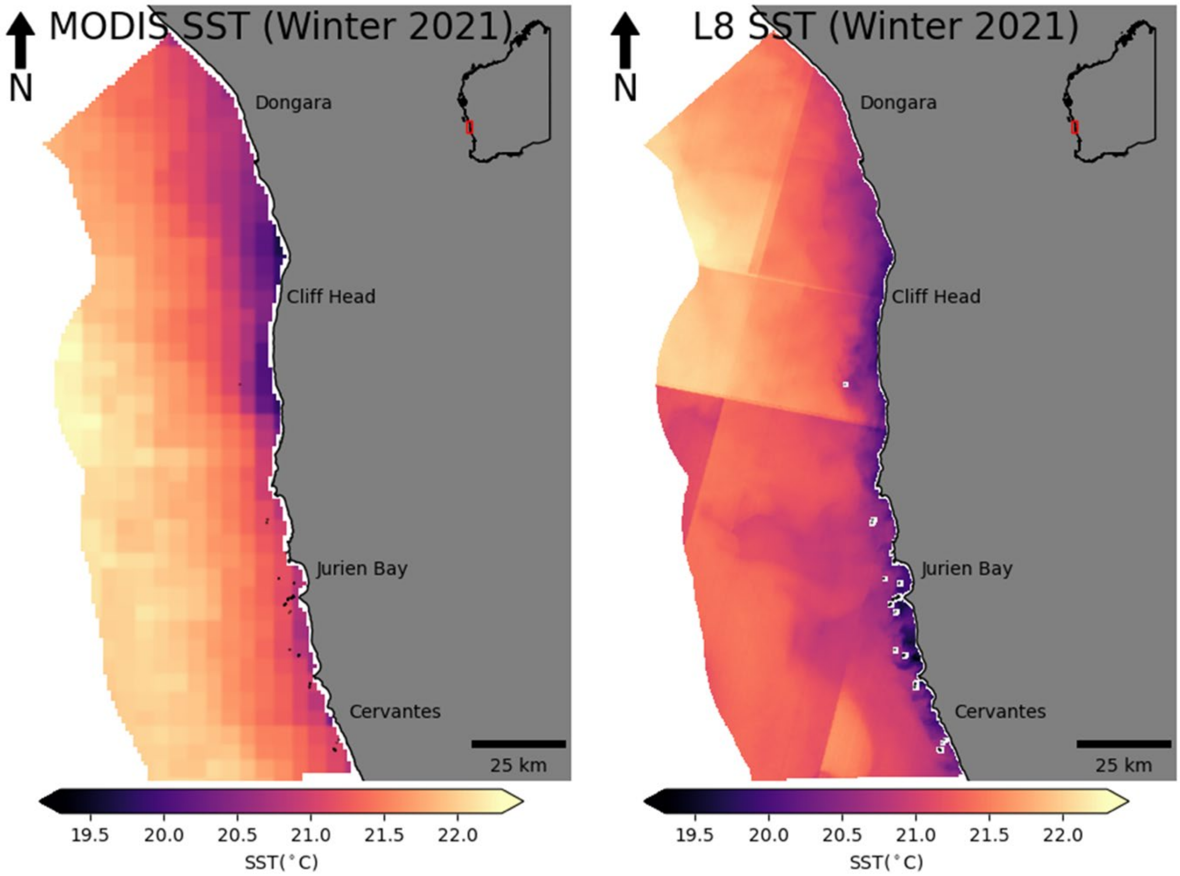

Remote sensing of sea surface temperature across the West-coast Bioregion. Image Stanley Mastrantonis.

Summary

The remote sensing of sea surface temperature anomaly has previously been used as a tracer for submarine groundwater discharge (SGD) upwelling. An expert workshop evaluating synthesis and field methods to study the influence of SGD across the Western Australia's West Coast Bioregion and potential impact on the Western Rock Lobster (WRL) and the West Coast Rock Lobster Managed Fishery (WCRLMF) made a series of recommendations for future studies. One of these was the application of remote sensing (RS) to detect sea surface temperature anomaly as a method to identify current or historical areas of SGD at medium to large scales (10-100's km). Previous studies have found SGD emergence can occur along the land/sea interface along the coastal margin. These studies have predicted that, given the typically hyper-stable temperature of SGD, SGD emergence should appear cooler in warm seasons and warmer in cool seasons, and can be visible in RS analysis of nearshore sea surface temperatures. At four key locations across the WCRLMF, where the monitoring

of settlement, recruitment and catch of WRL is well established and the influence of SGD is suspected, we used available historical RS data from Landsat 8, and analysed approximately six years of available imagery across warm and cool seasons. In contrast with other studies, we found thermal remote sensing is unlikely to a useful indicator of SGD at these locations because of land heat contamination at the land-sea interface. It has previously been acknowledged that this method can be challenging in regions with complex oceanographic regimes or with weaker SGD flows. We found that, despite being one of the main expert workshop recommendations, remote sensing of sea surface temperature anomaly, is unlikely to be a useful tracer of SGD at key locations because of land heat contamination at the land-sea interface.

Introduction

Remote sensing of sea surface temperature anomaly has been proposed to be useful for the large-scale (i.e. 10-100 km) characterization of submarine groundwater discharge (SGD) in coastal (Nandimandalam, Sharma, and Alagappan 2023) and freshwater systems (Mallast et al. 2014). These studies have previously hypothesised that given the typically uniform temperature characteristics of SGD, that areas of emergence in coastal waters should appear cooler in warm seasons and warmer in cool seasons (Wilson and Rocha 2012). However, previous studies have also noted that land heat contamination can obscure such characterization, and the utility of this approach can be influenced by the typical magnitudes of SGD occurring within a location (Varma et al 2010).

An expert workshop tasked with proposing synthesis and field methods with which to investigate to impact and role of SGD flows on the ecology of Western Rock Lobster (WRL) and therefore potential management implications for the West Coast Rock Lobster Managed Fishery (WCRLMF), provided a series of recommendations. One of these recommendations included the use of remote sensing of sea surface temperature anomaly to characterise and detect SGD (see Workshop summary).

This study set out to evaluate the utility of remote sensing of sea surface temperature anomaly, across four locations across the West Coast Bioregion. Location were chosen, where consistent remote sensing data existed and where the monitoring of settlement, recruitment and catch of WRL is well established and currently used to inform the WCRLMF (De Lestang et al. 2012).

Methods

Study area

Four study sites on the mid-west coast of Australia were selected as they represent an important fishery zone for the Western Rock lobster fishery and are actively monitored with in situ sampling. The sites spanned from Port Gregory (114.26°E 28.19°S) at the northernmost site to Lancelin (115.29°E 31.01°S) as the southernmost site, with Dongara (114.91°E 29.26°S) and Jurien Bay (114.99°E 30.26°S) in-between.

Remote sensing of sea surface temperature

Surface reflectance collections are sourced from Earth Engine for the Landsat 8 OLI/TIRS. Images are filtered to ensure that only images with less 10% cloud contamination are included. The radiance of the thermal bands are extracted from the collection in:

$$\frac{W}{m^2}\ sr\ .\ \mu m/DN$$

, where W are Watts, m2 denotes square meters, sr refers to steradians, μm signifies micrometres, and DN represents the Digital Numbers of the pixels. The radiance bands are multiplied by a scaling factor (0.001) to convert from integer DN to floating point radiance values. The radiance is then converted into SST (in °C) through the following transformation (Vanhellemont 2020):

$$T = K2/ln\ (\frac{K1}{ls} + 1)$$

Where K1 and K2 represent the minimum and maximum achievable radiance for the thermal bands extracted from the collection metadata. ls Represents the per-pixel radiance, which has been converted from Top-of-Atmosphere (TOA) at-sensor Brightness Temperature to surface temperature.

Sea surface temperature (SST) anomalies are typically calculated by subtracting an SST climatology across a range of years (e.g. 30 years) from a new SST observation. However, this is not possible for many RS data sets which typically either have time-series that are too short to construct a reliable climatology or have inconsistencies in time-series data due to cloud cover or weather conditions inferring with data collection (e.g. Landsat 8, Mastrantonis et al. 2024). Therefore, to evaluate the use of RS sea surface temperature to detect temperature anomalies we simply present here the best available images across cool and warm seasons at each location to provide an evaluation of any seasonal temperature anomalies. The results show areas where the sea-surface temperature was warmer (shades of yellow) or colder (shades of blue) relative to each sample.

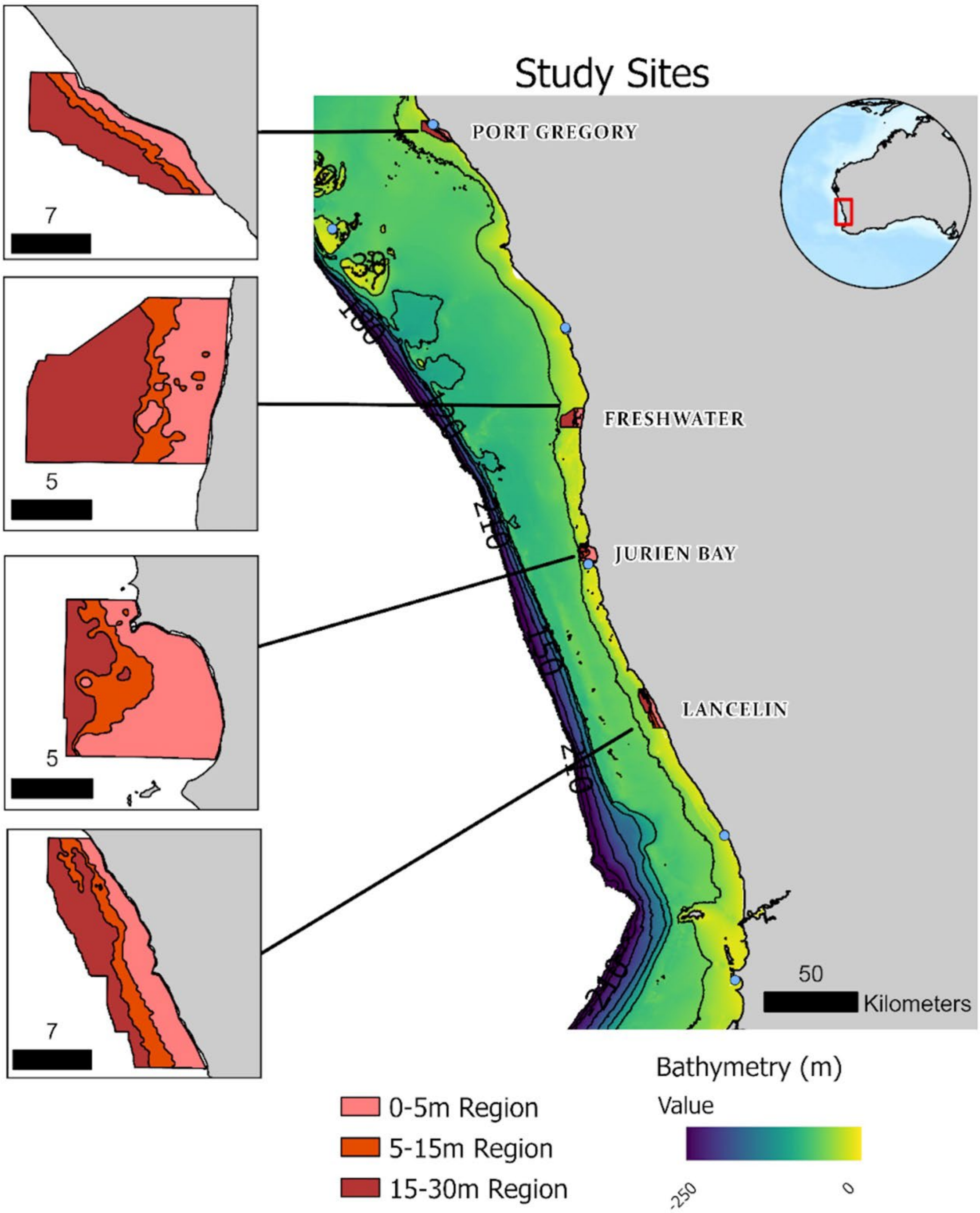

Figure 4 Study locations span the WCMF West Coast Bioregion, study locations have been shown with 0-5m regions, 5-15m, and 15-30m extents. Bathymetry (m) data were sourced from Geoscience Australia's Bathymetry and Topography Grid (Whiteway 2009). Contour lines represent 30 m depth intervals.

Results

Analysis of over six years of remote sensing sea surface temperatures at four study locations across the WCRLMF found consistent evidence of land heat contamination along the land-sea interface (Figure 5 - Figure 8). This "heat-island" effect was seen to consistently obscure the temperature signals along the land-sea interface. Jurien provides a strong demonstration of this heat effect where the small island within the bay (Favorite Island; -30.282, 115.007) senses as a thermal hotspot during warmer months across all years. The thermal conductivity of the small island reflects highly in the remote sensing imagery and, despite the high thermal inertia of water, contaminates the sea surface around the island (Figure 7). The same results can be seen at Lancelin where the Edwards Island Nature Reserve (-31.007, 115.316) shows a high degree of thermal conductivity, influencing the surrounding water (Figure 8). Conversely, in the winter months the land-sea interface presents cooler than average SST readings when compared to deeper regions, and hotspots created by the islands are no longer apparent in the imagery. Thermal imagery for winter months is sparse due to cloud contamination, thus, this pattern is challenging to detect, but from the imagery available during the colder months, we can detect a slight cooling effect of the land influencing the coastal sea surface.

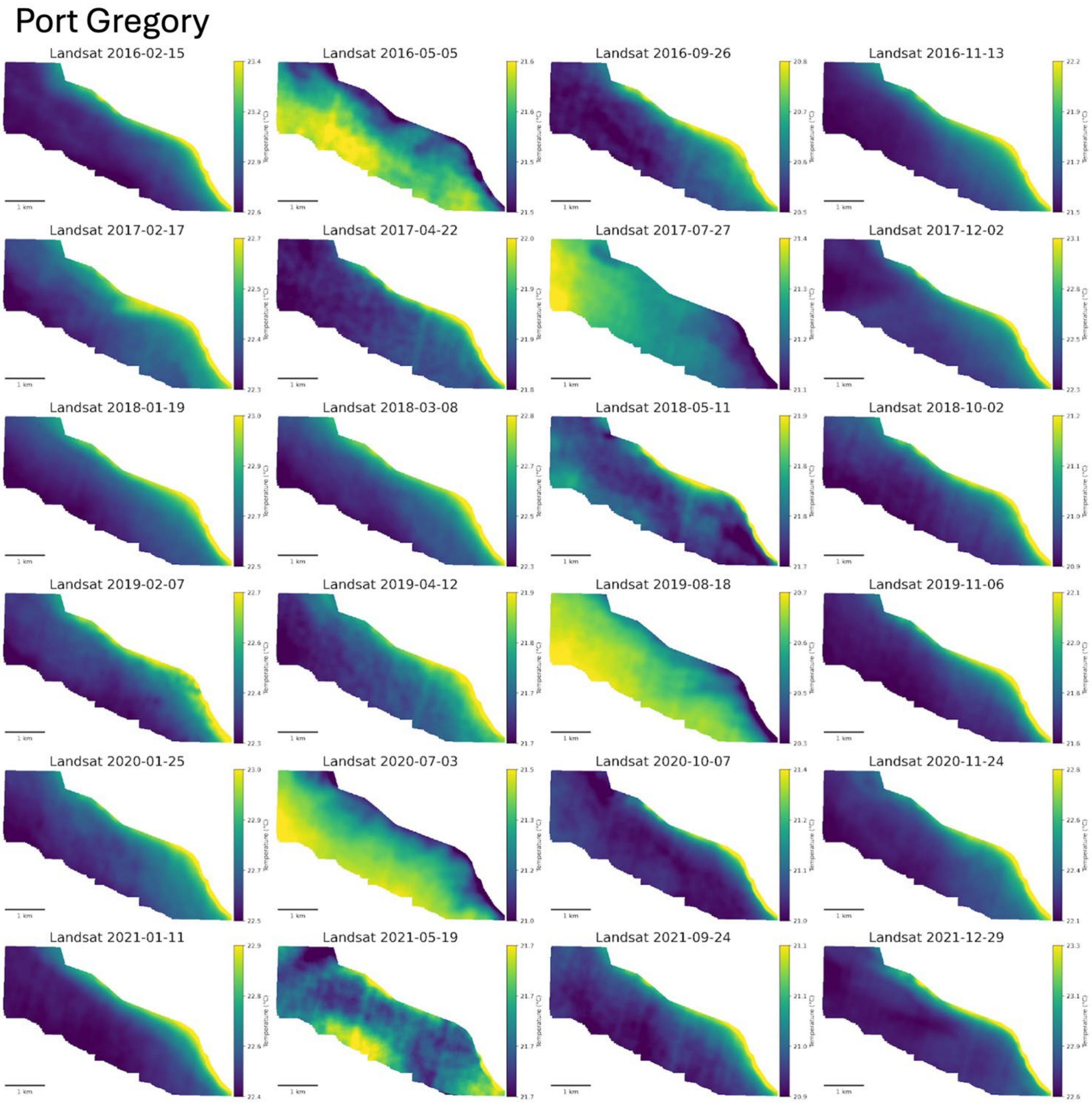

Figure 5 Sea surface temperature at Port Gregory from available Landsat imagery between 2016 and 2021.

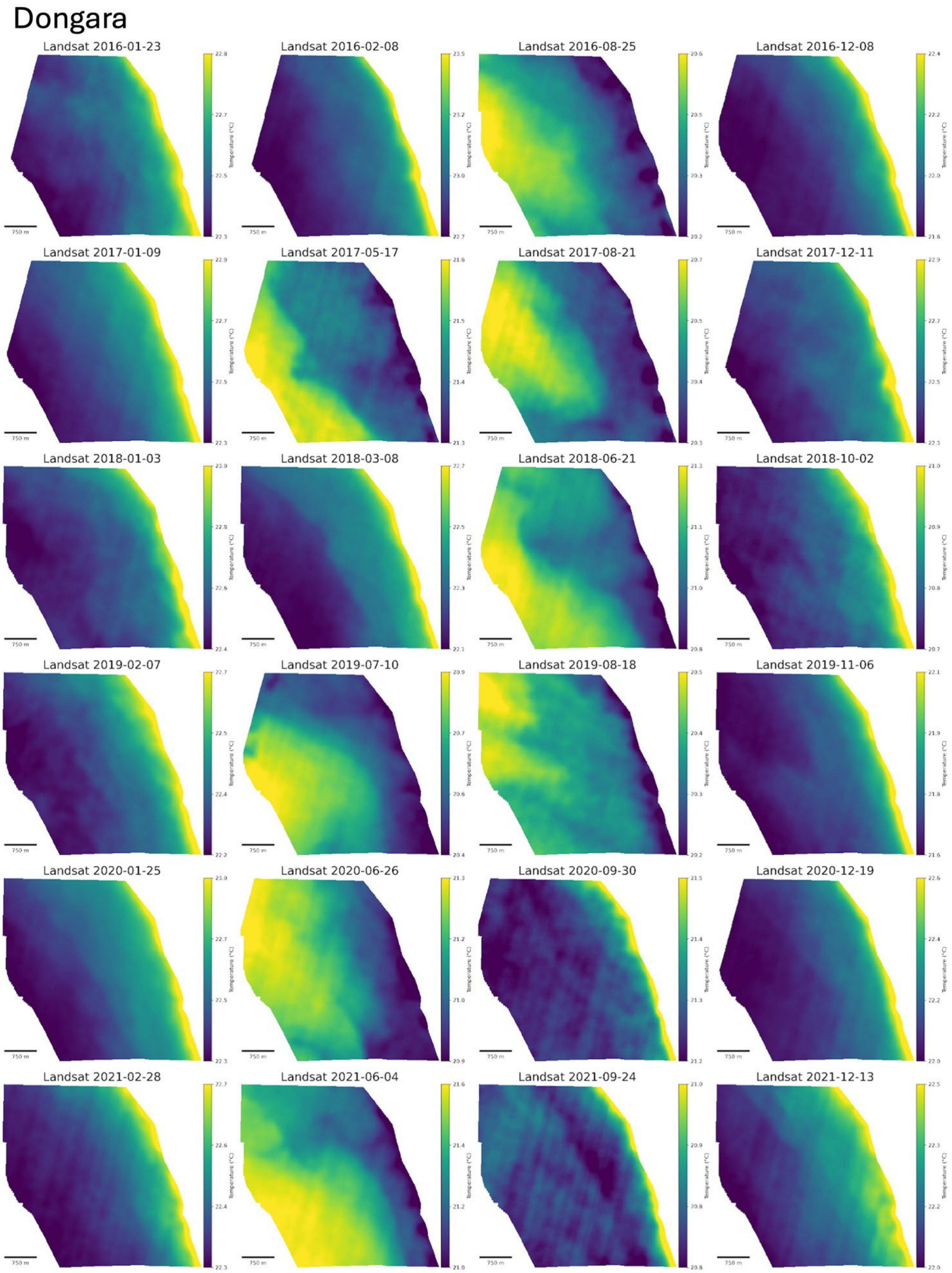

Figure 6 Sea surface temperature at Dongara from available Landsat imagery between 2016 and 2021.

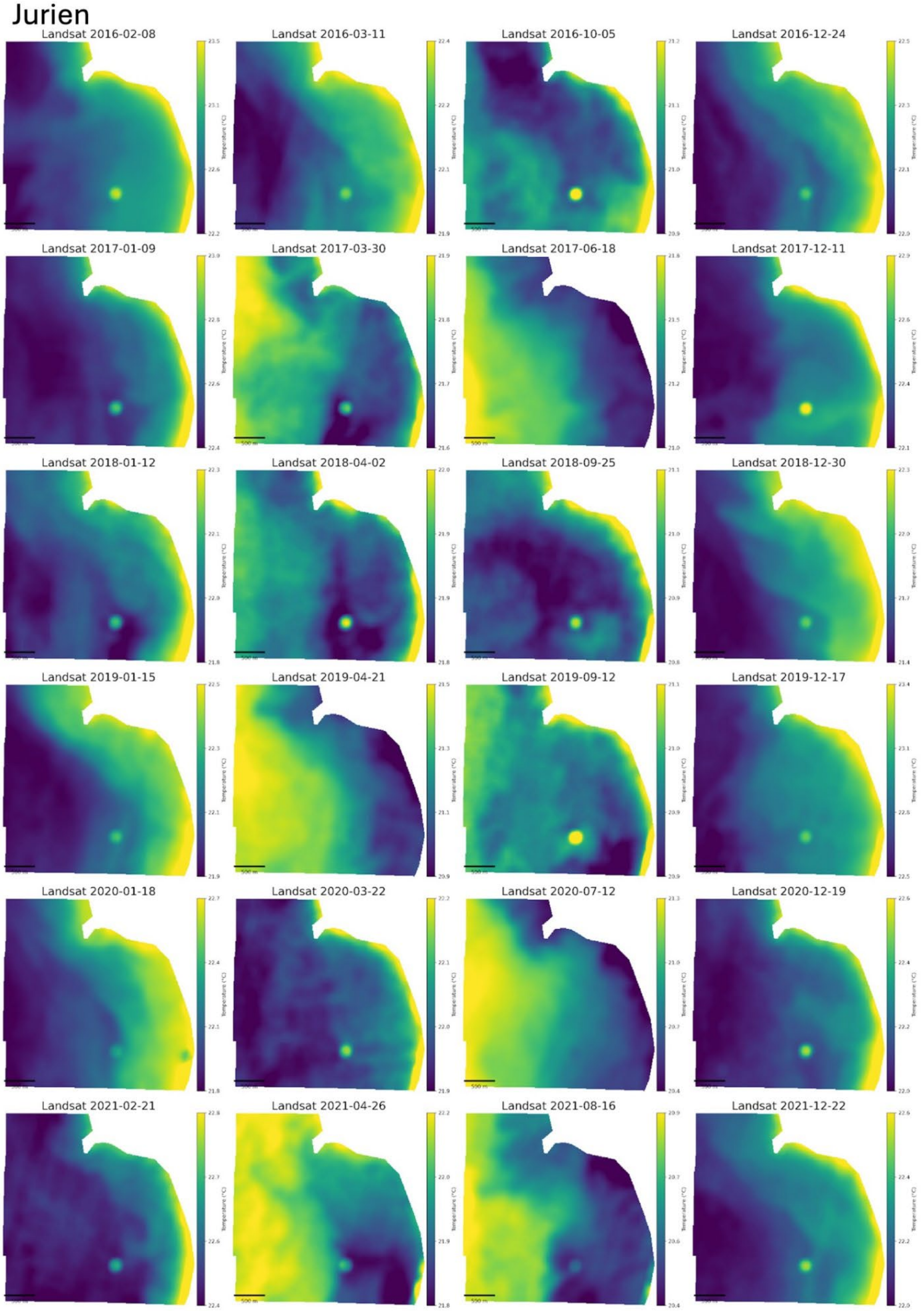

Figure 7 Sea surface temperature at Jurien from available Landsat imagery between 2016 and 2021. Note that the mostly consistent warmer spot towards the south of the location is the land of Favourite Island.

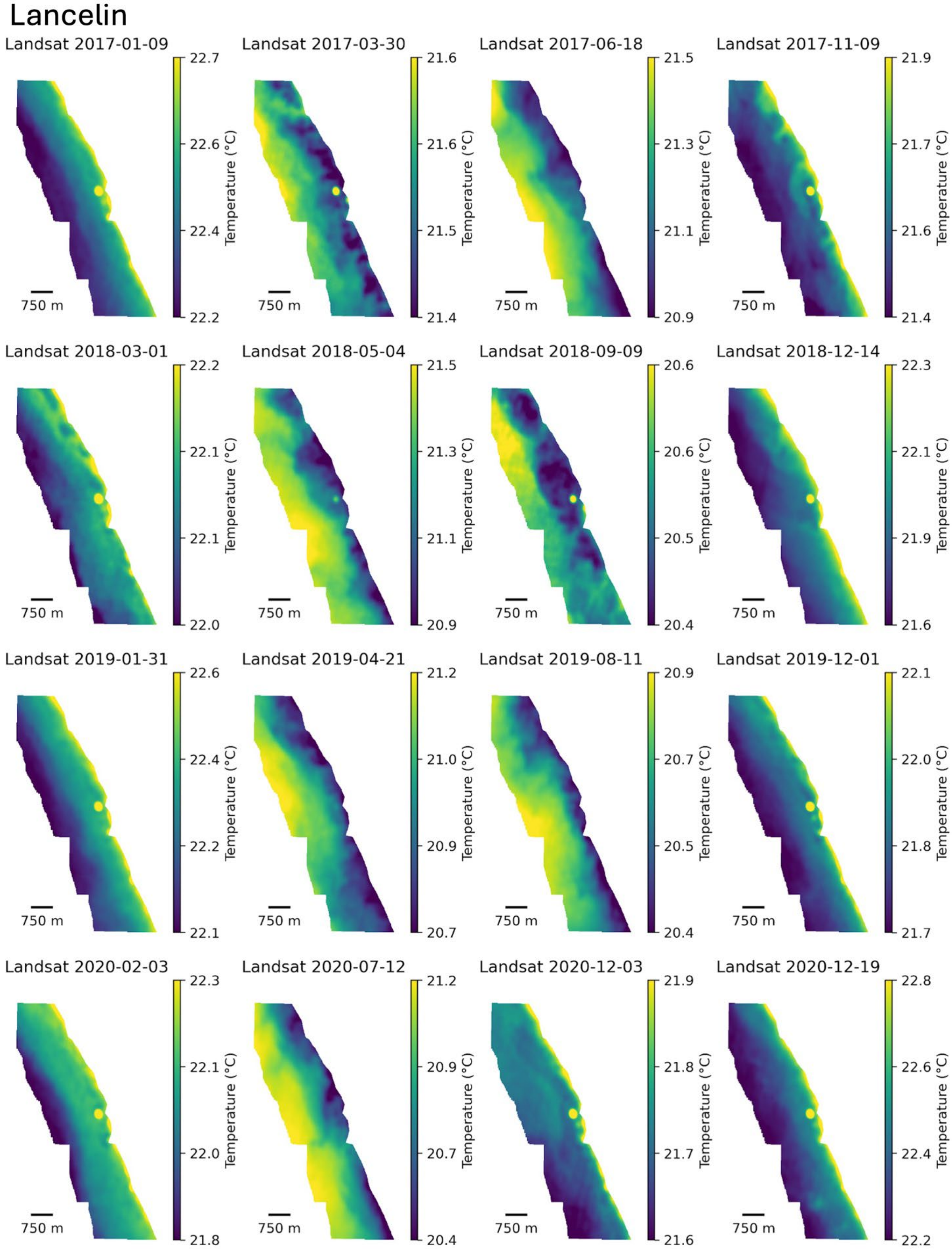

Figure 8 Sea surface temperature at Lancelin from available Landsat imagery between 2016 and 2020. Note that the mostly consistent warmer spot towards the centre of the location is the land of Lancelin Island.

Discussion

At four locations across the West Coast Bioregion, and where the monitoring of settlement, recruitment and catch of WRL to inform the management of the WCRLMF is well established (De Lestang et al. 2012), we found little evidence that remote sensing of sea surface temperature anomaly would provide a useful proxy of submarine ground water (SGD) flows. This is despite other studies from both the West Coast Bioregion (Varma, Turner, and Underschultz 2010) and internationally (Nandimandalam, Sharma, and Alagappan 2023) using remote sensing of sea surface temperature anomaly to infer SGD flows in coastal systems. Instead, we found that, assuming that SGD flows would be greatest at the land-sea interface, substantial land heat contamination is occurring consistently at these locations that would mask any temperature signals of SGD flows.

It is useful to note that previous studies documenting SGD flows with remote sensing of sea surface temperature anomaly (Wilson and Rocha 2012; Nandimandalam, Sharma, and Alagappan 2023), were in locations where the likely flows of SGD are typically 1-2 orders of magnitude greater that those predicted to occur along the West Coast Bioregion (Costall et al. 2020). The study that previously suggested remote sensing of sea surface temperature within Geographe Bay, in the West Coast Bioregion, found only limited evidence of SGD and acknowledge that the thermal effects of the adjacent landmass could be obscuring the thermal signature of these flows (Varma, Turner, and Underschultz 2010). It is possible that the perceived influence of SGD on SST within Geographe Bay proposed by Varma et al. (2010) was infact the combined effect of land heat contamination, wind waves and sun glint. Wind waves are prominent in RS records from Geographe Bay and can obscure reflectance and cause diffuse scattering of thermal irradiance, resulting in anomalous readings. Wind waves will interact the effects of sun glint across water, further confounding remote sensing and limiting the reliability of RS data (Kay et al. 2009, Li et al. 2020), as has been found in previous studies across the West Coast Bioregion (Mastrantonis et al. 2024).

Despite being one of the main workshop recommendations for field survey methods for the large-scale (10-100 km) identification of SGD flows, we found that remote sensing of sea surface temperature anomaly, is unlikely to be a useful tracer of SGD at key locations to the West Coast Bioregion or the WCRLMF, likely due to land heat contamination at the land-sea interface. Thermal remote sensing of SST is challenging at fine-scale resolutions (<1 km, Kay et al. 2009). Most fine resolution sensors have been developed for terrestrial applications and imagery has been calibrated for accurate irradiance over land. Irradiance and reflectance anomalies can occur in coastal imagery as a result of exiting calibrations being done to optimise measurement of terrestrial systems, and this has been document in the Landsat Known issues under "Overcorrection of aerosol path radiance in Landsat 8-9 Collection 2 Surface Reflectance resulting in nonphysical values over bright surfaces and over water" section (https://www.usgs.gov/landsat-missions/landsat-collection-2-known-issues#SR). Future endeavours to detect SGD from aerial sensors could be achieved through bespoke aerial sensors such as Hydrosat, but the issues of land heat contamination would like persist. As mentioned above, many other international studies that have documented the utility of remote sensing of sea surface temperature anomaly to detect SGD flows have also been at locations where the magnitude of groundwater flows are much larger (refs), however, given the long-term changes in regional hydrology across the West Coast Bioregion (see Supplementary Materials 1), due to land use change and decreasing winter rainfalls (see Costall et al. 2020; Priestley et al. 2023) such coarse-scale methods may be increasingly unsuitable in a drying climate.

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Survey design: Multi-disciplinary and multi-sensor survey of submarine groundwater discharge at key locations of interest within the West Coast Bioregion of Western Australia

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Ground water spring on intertidal reef flat at 7 Mile Beach with confirmed radon content. Photograph Tim Langlois.

Summary

Here we propose a multi-disciplinary and multi-sensor approach to investigate the influence of submarine groundwater discharge (SGD) on coastal ecosystems within Western Australia's West Coast Bioregion, and in particular the influence of these flows on Western Rock Lobster (WRL) ecology, settlement processes and recruitment into the West Coast Rock Lobster Managed Fishery (WCRLMF). The primary goal is to address three key questions regarding the ecological significance of SGD, its spatial variability, and the extent of areas affected identified by a multi-disciplinary workshop convened on this topic.

The proposed study emphasises a robust survey design, utilising spatially balanced data collection and leveraging existing information like LiDAR surveys and hydrological data to optimise efficiency and target areas with potential SGD hotspots. The proposed approach combines broad-scale surveys with

targeted investigations of paleochannels and adaptive sampling to effectively map SGD extent and hotspots.

A multi-sensor strategy is outlined, employing CTD sensors on an ROV for broad-scale and targeted surveys, followed by ground-truthing with discrete water sampling and radon gas detection. The use of an ROV would enable efficient data collection, whilst avoiding occupational safety restrictions associated with diving.

The proposed methodology is adaptable to various locations, illustrated through a survey design example for the Dongara region, and could be used at locations across the WCRLMF, where the monitoring of settlement, recruitment and catch of WRL is well established and the influence of SGD is suspected. This design incorporates spatially balanced sampling with adaptive principles and targeted paleochannel investigations.

The research aims to establish a benchmark for future studies of change, identify SGD hotspots. Such a survey will be a first step towards understanding SGD's ecological influence across the West Coast Bioregion, and in particular the influence of these flows on Western Rock Lobster (WRL) ecology, settlement processes and recruitment into the West Coast Rock Lobster Managed Fishery (WCRLMF).

Broad objectives

This proposed multi-disciplinary and multi-sensor survey of submarine groundwater discharge is designed to address the three priority question put forward by the expert group workshop on the influence of submarine groundwater discharge (SGD) on the ecology of coastal ecosystems across the West Coast Bioregion of Western Australia, and in particular the influence of these flows on Western Rock Lobster (WRL) ecology, settlement processes and recruitment into the West Coast Rock Lobster Managed Fishery (WCRLMF).

These questions are: 1. What is the significance of SGD effects to marine assemblages, WRL and the WCRLMF? 2. What is the spatial variability of SGD; identify hotspots where SGD is important? 3. What is the extent of areas affected by SGD?

An important component of these questions is the recognition of the need to map SGD flows across key locations of interest. To best inform our understanding of the influence of SGD on WRL, studies should be focused at locations across the WCRLMF, where the monitoring of settlement, recruitment and catch of WRL is well established and the influence of SGD is suspected. Creating maps of SGD flows at such locations will provide a benchmark for future studies of change and provide spatial information to locate future studies (Mastrantonis et al. 2024). In addition, maps for areas of interest will enable the highest priority question to be addressed, where mapping will allow the extent of SGD effects to be put into the context of the location of interest and the WCRLMF and West Coast Bioregion in general.

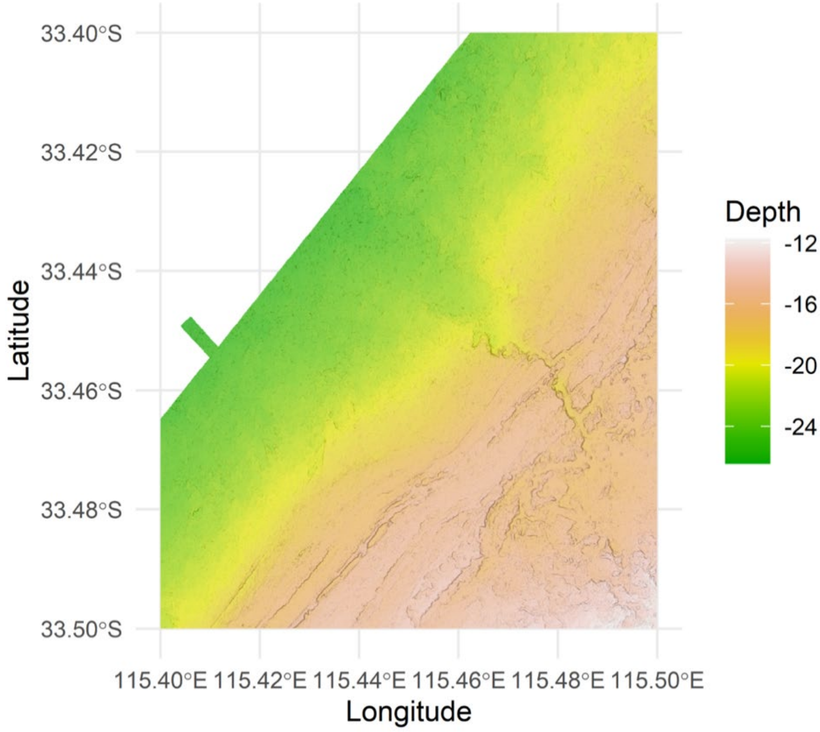

Figure 9 Paleochannel bisecting submarine coastal limestone formations in 20 m, West Coast Bioregion, WA.

Role of data synthesis in survey planning

Robust survey design to estimate extent relies on acquiring spatially balanced data (Mastrantonis, Langlois, et al. 2024), and to increase cost-efficient mapping pre-existing information can be used to bias the spatial data towards areas of interest (Foster et al. 2017) and where spatial variation may be greatest (e.g. strongest gradients in salinity will occur at the boundary of SGD). For example, SGD has been found to be concentrated along the edges of paleochannels, where they breach confining geological units, acting as a hydraulic connection to aquifers (Mulligan, Evans, and Lizarralde 2007). Recent coastal LiDAR surveys throughout the West Coast Bioregion have provide useful information on the location of marine benthic features and paleo channels (Figure 9). Combined with a synthesis of existing data (Table 4) on the regional variation of groundwater pressure along the coast (e.g. WA Water information reporting system), remote sensing of sea surface temperature anomaly (i.e. as a tracer for SGD upwelling), and expert knowledge on the presence of SGD (e.g. from consultations with fishers), such information can be incorporated into spatially balanced designs to cost-effectively map the extent and hotspots of SGD (Foster et al. 2017). With the objective that the modelling of the extent and hotspots of SGD will be able to be reliably predicted by detailed bathymetry and geophysical data (e.g. location of paleochannels) combined with broader scale information on hydrology (e.g. pressure fields of local aquifers).

Spatially-adaptive sampling approaches have also been demonstrated to be useful for survey of patchily distributed or clustered events (Pacifici et al. 2016) such as SGD. A combination of a spatially balanced survey design with adaptive principles to enable field evidence of SGD to add additional cluster sampling to better determine the extent of any SDG hotspots will likely provide the cost-effective solution for the mapping of potentially rare occurrences of SGD.

Lessons from pilot testing of recommended field methods

The most recommended field method from the expert led workshop was the use of radon gas detection. The presence of radon gas is an established method for tracing submarine groundwater discharge (Moore 2010). Through the current project, a pilot study was conducted from a known ground water spring along the Irwin River at Strawberry Bridge, ~40 km inland, where replicate samples of surface water were tested for the presence of radon gas following the RAD7-H2O technique laid out in Alharbi et al. (2015). Pilot testing successfully demonstrated repeatable radon detection at the ground water source (Figure 10) and within 20 km downstream, but surface water testing at the mouth of the Irwin River, and along a transect from Port Denison to Cliff Head and Freshwater Point found no detectable trace of radon in surface waters. However, surface spring testing at 7 Mile Beach did find repeatable radon detection.

This pilot study demonstrates one of the common issues in studies of SGD, in that although radon is an excellent trace of groundwater it typically dissipates very quickly in coastal waters (Dulaiova et al. 2005). Unfortunately, the usefulness of radon as a tracer is limited by the time-consuming nature of collecting individual samples and traditional analysis schemes. More recently, investigators are proposing multi-sensor approaches to improve field efficiency, including other isotopes and oceanographic tracers (Dulaiova et al. 2010).

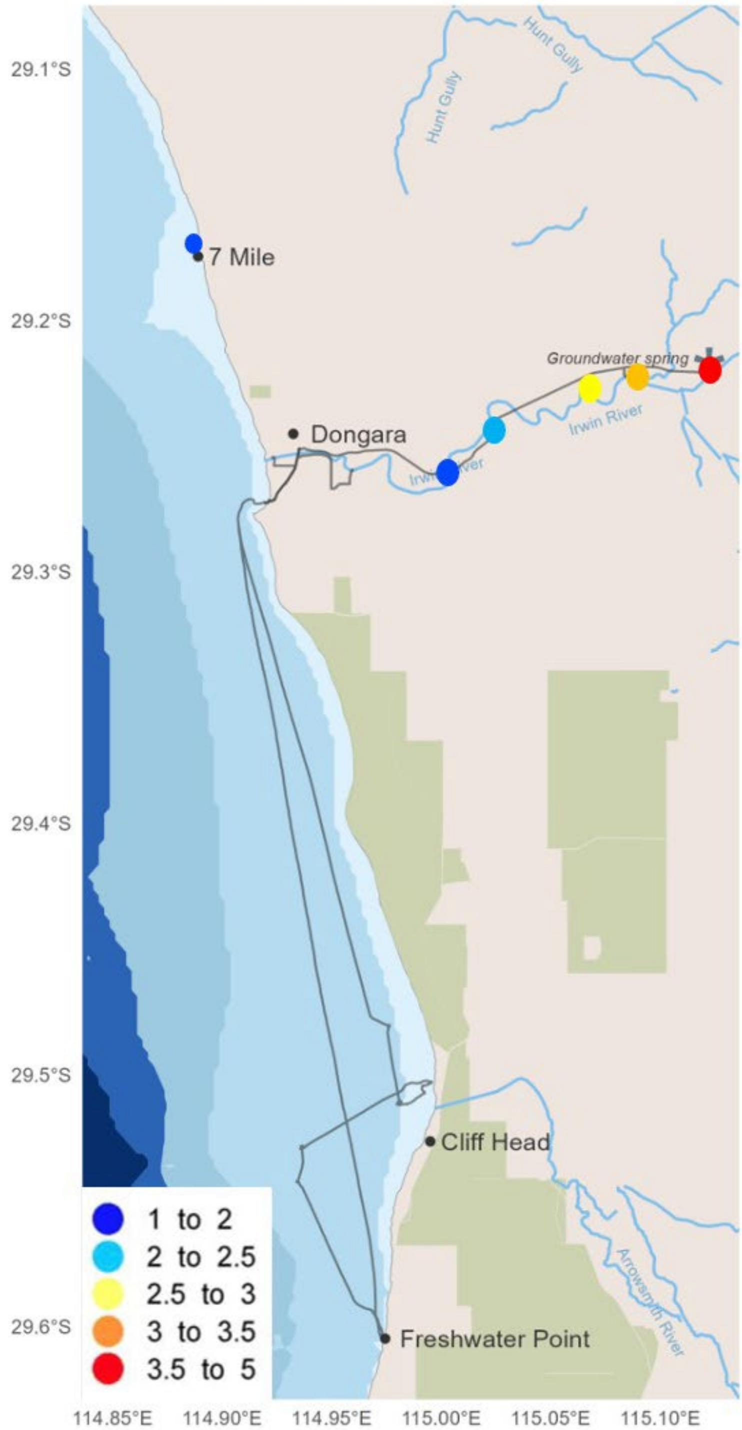

Figure 10 Pilot Radon gas survey from groundwater spring on the Irwin River, 7 Mile Beach and vessel transect from Port Denison to Cliff Head and Freshwater Point. Radon in dpm L^{-1}.

Proposed multi-sensor approach

Mapping SGD extent and hotspots at key locations of interest will provide a benchmark for future studies of change and provide spatial information to locate future studies (Mastrantonis, Radford, et al. 2024). To map these areas using a spatially-adaptive survey design will require a suitable suite of sensors that could be used at broad and fine scales. In contrast to radon gas sensors, that require up to 3-5 minutes to process a single sample for detection (Alharbi, Abbady, and El-Taher 2015), CTD

(Conductivity, Temperature and Density) or salinity sensors provide instantaneous measurement. Therefore, we propose that a surface vessel deployed ROV, with underwater positioning system (USBL), would be used to complete seabed salinity and temperature readings across a spatially-adaptive sampling design for a survey area, in addition to targeted sampling of any paleochannels (Table 6). These surveys would be conducted as close as possible to the seabed or seabed feature surface, to account for the raid dilution of SGD. The advantage of an ROV over a diver, for these broad scale and targeted surveys is that the spatial extent of samples and required number of ascents would be logistically unfeasible based on health and safety procedures, whereas modern small-form ROVs have adequate manoeuvrability to be used to carry out complex sampling within close proximity to the seabed whilst being 'live-boated' from an un-anchored support vessel in the appropriate weather conditions (Monk et al. 2024).

These broad and targeted surveys would produce an initial map of the extent and hotspots of lower salinity/temperature flows that could then be ground-truthed for the presence of SGD using either an ROV or diver to collect discrete water samples directly from the seabed for radon testing (Table 6), either using Niskin Bottle water sampler or a submersible pump and flexible pipe to collect water directly from the seabed up to the support vessel for radon testing (Shellenbarger et al. 2006).

Table 6 Multi-sensor approach for SGD survey across survey location.

Survey stage	Survey design	Sensor platform	Sensors and recording
Broad scale	Spatially-adaptive	ROV deployed from vessel	CTD with live data feed to vessel
Targeted	Target transects along paleochannel edges	ROV deployed from vessel	CTD with live data feed to vessel
Ground truthing	Target low salinity hotspots	Diver or ROV collected discrete water sample, with pump to surface vessel	Water pumped up to RAD7 – radon sensor on vessel

Survey platform and instruments

Modern small-form ROV now provide a capable underwater sampling platform for a variety of applications, with adequate mobility to conduct predefined and opportunistic sampling across a range of continental shelf depths (Foster et al. 2019). The University of Tasmania currently uses a range of ROVs including a BoxFish ROV built in New Zealand. Such ROV can have a range of positioning beacons (e.g. USBL), sensors (e.g. CTD) and tools (e.g. water sampler) built into them (Figure 11) which would be well suited to all stages (i.e. Broad scale, Targeted and Ground-truthing) of the proposed multi-disciplinary and multi-sensor survey.

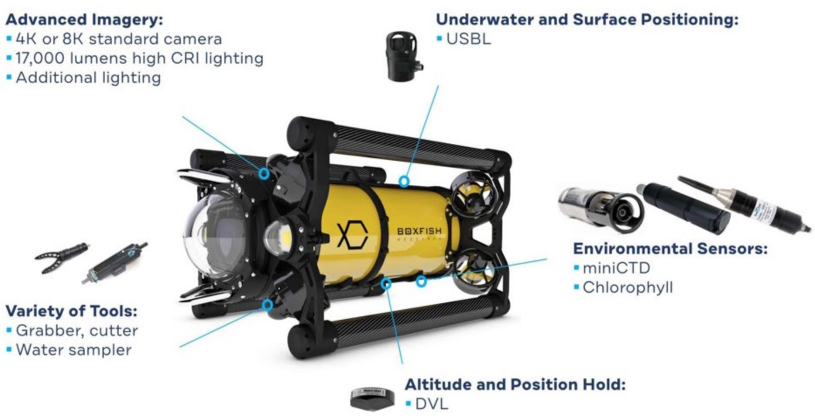

Figure 11 Remotely Operated Vehicle equipped with oceanographic and biological sensors. Image courtesy of Boxfishrobotics.

Study location and survey design

The proposed multi-disciplinary and multi-sensor survey for SGD could be adapted to any location. Here, we provide an example of a survey design, using available high-resolution LiDAR derived bathymetry, for the Dongara region between 7 Mile Beach and Freshwater Point (Figure 12). There is clear evidence of paleochannels and distinct bathymetric features within this location (Figure 12 a, b and c), these geological features would be a priority for inclusion within both the broad scale and targeted survey components (Table 6). Using the Field Manuals for Marine Sampling to Monitor Australian Waters (Przeslawski et al. 2023) and recommendations for spatially balanced survey design (Foster et al. 2017).

Here we have created a spatially balanced survey design from 1 to 20 m depth, designed to oversample areas of high variance in bathymetric relief, where bathymetric relief is broken into four strata and the highest relief strata is oversampled (i.e. following a distribution of sampling effort to 60%, 10%, 10% and 10%). The rate of oversampling and total number of samples can be adjusted based on the questions and logistical constraints of field work (Figure 13). Adaptive sampling and paleochannel targeting would be additional to these sample locations.

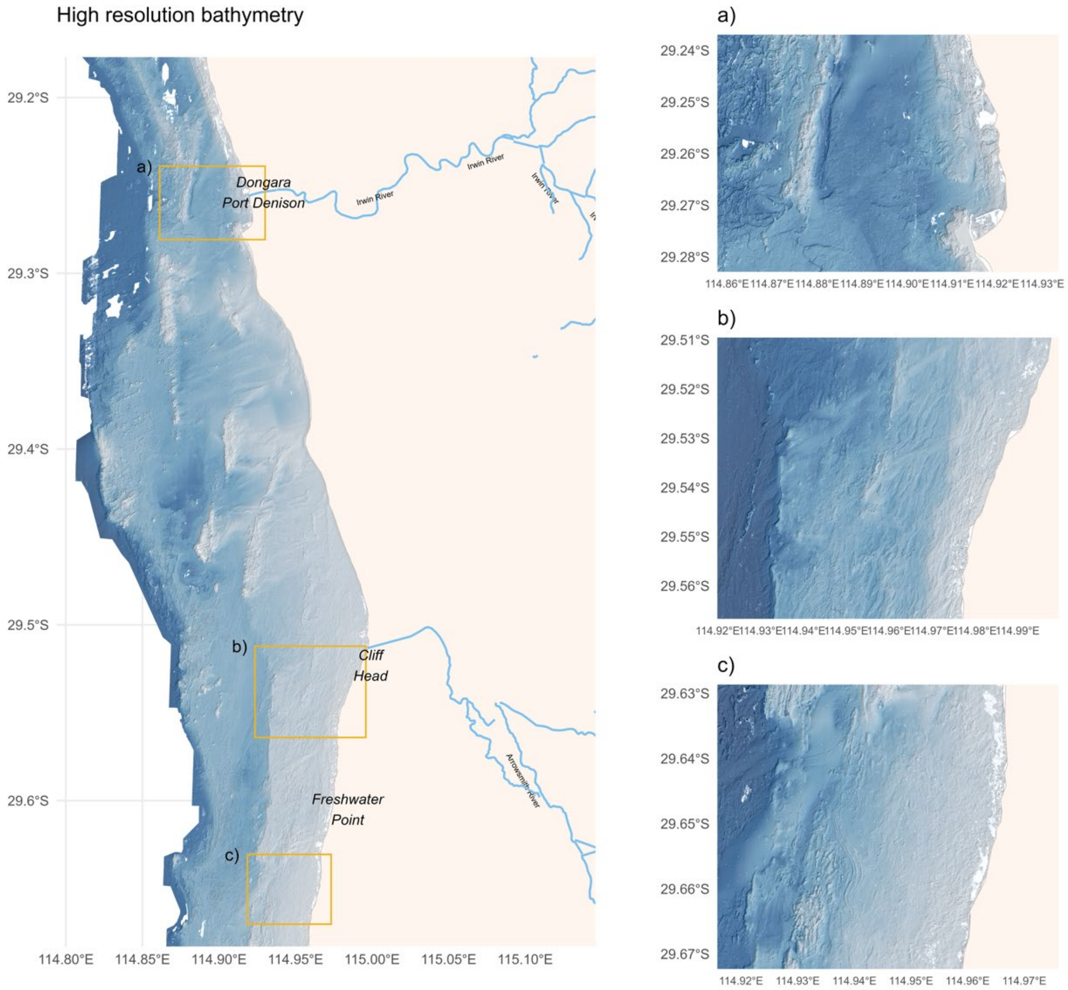

Figure 12 Bathymetric detail of paleochannels and high-relief features at three areas within a proposed study location.

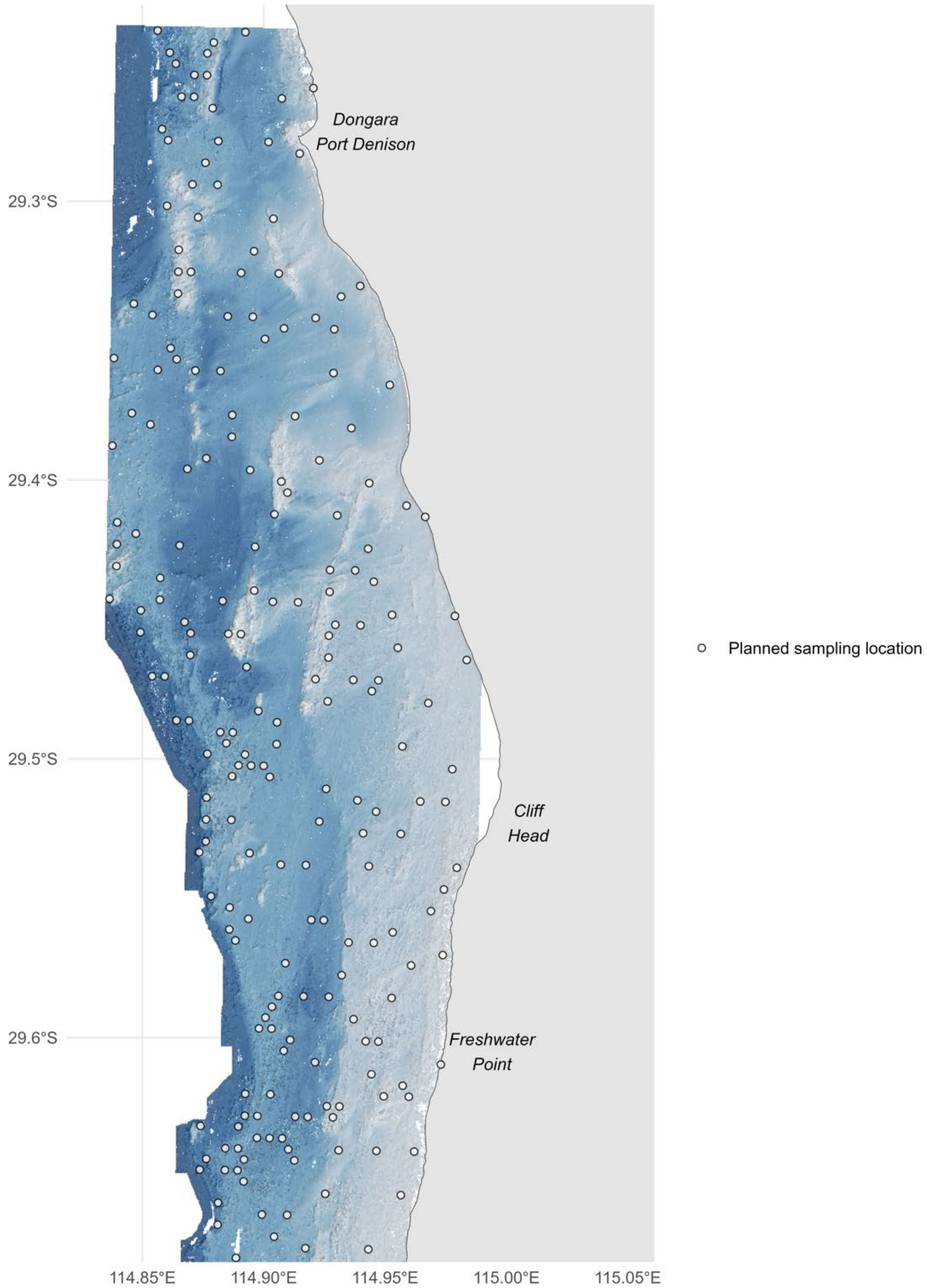

Figure 13 Example spatially balanced survey design from 1 to 20 m depth, designed to oversample areas of high variance in bathymetric relief. Adaptive sampling and paleochannel targeting would be additional to these sample locations.

Conclusion

The overall objectives of this project, was to design a study to better understand how SGD may influence the ecology of Western Rock Lobster (WRL), its settlement processes and recruitment into the West Coast Rock Lobster Managed Fishery (WCRLMF). This proposed multi-disciplinary and multi-sensor survey framework offers a robust approach to investigate Submarine Groundwater Discharge (SGD) for locations of interest across the West Coast Bioregion of Western Australia, in particular for locations where the monitoring of settlement, recruitment and catch of WRL is well established and the influence of SGD is suspected.

Based on recommendations from the expert workshop, documented in this report, the survey would integrate data synthesis, to inform survey design, and then apply a multi-sensor and multi-stage approach in the field to map the extent and hotspots of SGD for a chosen study location. Such an approach would meet two on the highest priority research questions identified by our expert workshop, the identification of extent and spatial variability, whilst providing a solid benchmark with which to start studies to investigate the highest priority, which is to understand the significance of SGD for marine ecosystems and fisheries species.

Spatially balanced survey designs, informed by pre-existing data and expert knowledge, allow for efficient and targeted data collection (Foster et al. 2017). The use of multiple sensors, including CTD instruments, and fluorometers, on a ROV platform to complete initial characterization followed by confirmation of SGD presence with radon sensors should provide a cost-effective but robust approach. The integration of adaptive sampling further enhances its flexibility, allowing for real-time adjustments based on field observations and emerging patterns. While the Dongara region example illustrates its application in a specific context, the methodology could be tailored to suit any location.

It is important to acknowledge the challenges associated with mapping and studying SGD, such as the rapid dissipation of radon gas in coastal waters (Mulligan, Evans, and Lizarralde 2007). A variety of other international studies have succeeded in measuring and documenting SGD in coastal locations (e.g. Shellenbarger et al. 2006; Dulaiova et al. 2010; Duque, Russoniello, and Rosenberry 2020), however, the pilot study presented here only found traces of radon at springs on the shore and inland but not in coastal waters. Based on consultations with domain experts in the workshop documented in this report, we propose that the combination of an ROV sampling platform using oceanographic sensors (e.g. CTD) to detect evidence of SGD, combined with a spatially adaptive sampling approach and ground truthing with in-field radon measurement is likely the most cost-effective approach to establish the spatial extent and hotspots of SGD within any typical coastal study location of the West Coast Bioregion. Such a mapping exercise would provide the benchmark on which to base future research to understand the significance of SGD for marine ecosystems and fisheries species across the West Coast Bioregion. This understanding is particularly crucial given the documented changes in regional hydrology (see Costall et al. 2020; Priestley et al. 2023), attributed to decreased winter rainfall and increased temperatures, which are likely impacting SGD flows and which can be a potentially important nutrient supply (Shellenbarger et al. 2006) in particularly within the coastal ecosystems of the West Coast Bioregion which is typically low in essential nutrients compared to many other regions of the globe (see Lourey, Dunn, and Waring 2006).

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Conclusion

This project provides a first step to increasing our understanding of the influence of submarine groundwater discharge (SGD) and freshwater flows on the ecology of Western Rock Lobster (WRL), its settlement processes and recruitment into the West Coast Rock Lobster Managed Fishery (WCRLMF). Recruitment of Western Rock Lobster has been recognised to be largely driven by environmental conditions (Caputi 2008; Kolbusz et al. 2022), with increasing recognition of the role of aquatic vegetation (Mastrantonis, Radford, et al. 2024), including seagrass (Brooker et al. 2022), but the role of freshwater and/or nutrients derived from submarine groundwater discharge from land is unknown. SGD is generally suspected to be a contributing factor to the broad composition of both algal and seagrass assemblages along the Western Bioregion of Western Australia (G. Kendrick, personal communication). Whilst there are as yet no studies documenting any mechanistic relationships with SGD in the Western Bioregion, we have reviewed various evidence globally (see (Johannes 1980; Shellenbarger et al. 2006). What is known across the Western Bioregion of Western Australia is that with land use change and long-term trends of decreasing winter rainfall and increasing winter temperatures (see Supplementary Information 1), SGD is likely to decrease and has been measured to have substantially decreased at some sites in the metropolitan region (Costall et al. 2020).

The expert workshop provided a suggested approach to synthesise existing information and to inform the selection of data collation and field methods. This workshop highlighted the need to map SGD flows across key locations of interest, as the first step to addressing the top three priority questions.

These questions are: 1. What is the significance of SGD effects to ecology of WRL, its settlement processes and recruitment into the WCRLMF? 2. What is the spatial variability of SGD; identify hotspots where SGD is important? 3. What is the extent of areas affected by SGD?

Creating maps of these flows will provide a benchmark for future studies of change and provide spatial information to locate focused studies. Where mapping will allow the extent of SGD effects to be put into the context of the location of interest and the Western Rock Lobster fishery and West Coast Bioregion in general.

From the workshop, one of the main recommendations for field survey methods was the remote sensing of sea surface temperature anomaly, as a large-scale indicator of SGD flows. However, after the workshop we conducted a study to evaluate this field method at key locations across the WCRLMF, but found thermal remote sensing is unlikely to a useful indicator of SGD because of land heat contamination at the land-sea interface (see Evaluation of Field Methods).

Another main recommendation for field work from the workshop, as a finer-scale indicator to identify SGD flows, was the use of radon gas detection in coastal systems. However, a pilot study demonstrated that although this method worked well to confirm SGD at known emergence points, it was not likely sensitive enough to detect SGD at the sea surface in well mixed coastal environments and instead we recommended that future assessments with radon gas should focus on sampling directly from the seabed, directly where SGD's are suspected to emerge.

The outcomes of the workshop, along with the findings of the pilot, indicated that we did not have a sufficient level of knowledge on which to base our investigation of the original objectives. Therefore, the project pivoted to instead use the recommendations of the expert workshop to design a future survey approach to better understand SGD processes within areas of interest across the West Coast Bioregion and to create a more informed understanding with which to plan for future studies.

Further development

This report proposes a synthesis, survey, platform and sensor design to survey submarine groundwater discharge, designed to address the priority question on extent and the occurrence of hotspots, but which will then inform future study of the influence of submarine groundwater discharge (SGD) on the ecology of coastal ecosystems across the West Coast Bioregion of Western Australia. The proposed methodology would be adaptable to any location and form a first step to better understand the potential ecosystem role of these flows and provide a baseline for future work to understand how SGD influences the productivity of Western Australia's coastal ecosystems and understand better the implications for WRL ecology, settlement and recruitment into the WCRLMF.

This proposed multi-disciplinary and multi-sensor survey of submarine groundwater discharge is guided by the most recent international research on SGD (see Costall et al. 2020) and by the Field Manuals for Marine Sampling to Monitor Australian Waters (Przeslawski et al. 2023), recommendations for spatially balanced survey design (Foster et al. 2017) and approaches for cost-effective ROV platforms (Monk et al. 2024). The recommended approach uses multi-disciplinary and multi-sensor sampling combined a spatially balanced survey design and was designed to be informed by data synthesis and expert knowledge, with adaptive approaches to identify and ground-truth any SGD hotspots.

Concluding remarks

There has been over 50 years of scientific research on the biology, ecology and behaviour of the Western Rock Lobster, *Panulirus cygnus* and in this time, we have learnt a substantial amount about this species and its dynamics as a fishery species. However, there are various acknowledge gaps in our understanding, and the influence of submarine ground water discharge (SGD) is a knowledge gap not only for Western Rock Lobster but for the entire marine ecology of the Western Bioregion of Western Australia. This project provides arguments as to why SGD is likely to be an important factor influencing the ecology of nearshore environments of the Western Bioregion, partly due to the unique oceanography and both generally low surface freshwater and terrigenous nutrient inputs across the region. Our expert workshop, pilot studies and evaluation of field methods have informed a suggested approach for the next steps of how to further our knowledge of this potentially important process. This project has highlighted that despite the wealth of knowledge about the Western Rock Lobster fishery and the Western Bioregion of Western Australia more broadly we have little understanding about a process that has a potentially important ecological role in structuring our nearshore marine ecosystems.

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Extension and Adoption

Project coverage

Draft media article – not yet released

Western Rock Lobster connection between land and sea: Study of groundwater flows and juvenile western rock lobster

Most of us agree that babies are small, cute and vulnerable. Some of us think the same of baby (juvenile) western rock lobsters which, after spending up to 11 months in the open ocean and measuring only 3 cm in length, find a home amongst marine plants along our coast.

Research is indicating that groundwater flows are an important source of nutrients in coastal ecosystems, especially in WA where we have limited surface river flows. These nutrients can be essential to the growth of coastal marine plants. Western Rock Lobster fishers are working with researchers to understand more about the role of groundwater flows along WAs coast.

John Fitzhardinge, a retired lobster fisher with many years' experience supporting research projects recalls: "In the 60's and 70's juvenile lobsters were more abundant around river mouths and we also suspected there was greater recruitment around groundwater flows, areas where fresh water comes up out of the seabed".

Tim Langlois from The University of Western Australia's Oceans Institute adds "juvenile lobsters are vulnerable to predators and we suspect they rely on thick beds of seagrass and marine plants for shelter. If groundwater flows improve their habitat, this may increase their survival".

Department of Primary Industries Regional Development principal research scientist Simon de Lestang said over the past 9 years the abundance of juvenile western rock lobster had varied dramatically in some areas.

"It is thought a marine heat wave in 2011 may have reduced marine plants and seagrass in some areas of the fishery, impacting on the survival rate of juvenile lobsters." he said. "In this project, we aim to understand the connection between the land and sea, and how groundwater flows could affect the survival of young lobster."

Funded through the Western Rock Lobster Industry's Partnership Agreement with the Fisheries Research and Development Corporation, the project will assess the role of groundwater flows on habitats and juvenile lobster at sites across the Western Rock Lobster fishery.


Juvenile Western Rock Lobster sheltering amongst seagrass. Photograph Daphne Oh


Juvenile Western Rock Lobster hanging onto a seagrass shoot Photograph Daphne Oh


Juvenile Western Rock Lobster amongst seagrass shoots Photograph Daphne Oh


Juvenile Western Rock Lobster hiding under seagrass debris Photograph Daphne

Supplementary information 1

The changing climate of the West Coast Bioregion of Western Australia and potential influence on groundwater flows

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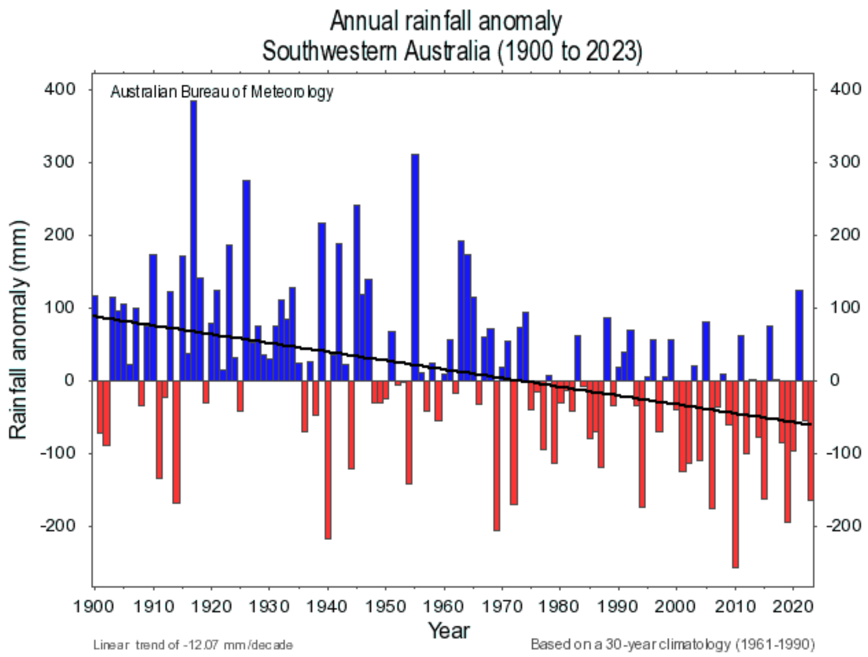

Image source [Australian Bureau of Meteorology](#).

Summary

This study examines hydrological changes in the Perth metropolitan area and broader climate trends in Southwestern Australia. Perth has experienced a substantial decrease in submarine groundwater discharge, attributed to increased groundwater extraction and reduced recharge rates. Land-use change, declining early winter rainfall, and increased surface evaporation due to warmer winters and shifts in rainfall patterns are implicated in this declining groundwater recharge.

Long-term climate data from the ACORN-SAT dataset (1910-present) reveals a clear warming and drying trend across the Southwestern region. Groundwater storage acts as a "memory" of past climatic conditions, and years of reduced winter rainfall can have lasting impacts on hydrogeology. Annual temperatures have risen while annual rainfall has decreased. Focusing on winter months, the trend of increasing temperatures and decreasing rainfall is even more pronounced. This pattern has significant implications for groundwater recharge, as lower winter rainfall coupled with warmer winter temperatures resulting in higher evaporation rates is suspected to lead to reduced recharge.

These findings highlight the complex interplay between climate change, land use, and groundwater resources. Understanding these interactions is critical for an effective understanding of SGD regimes, particularly in the face of a changing climate.

The changing climate of the West Coast Bioregion of Western Australia and potential influence on groundwater flows

Changing climate

Across the Perth metropolitan area, the hydrology has been reported to have changed significantly over the last 40-50 years, with both monitoring and modelled estimates indicating an approximately 50% decrease in submarine groundwater discharge (Costall et al. 2020; Ali et al. 2012). This change in hydrology has been attributed to increased ground water extraction and decreased recharge rates; through a combination of land use change, decreasing rain fall over the last 40-50 years (Figure 14) and increased surface evaporation from warmer temperatures (Figure 15). The prediction and evidence of increased surface evaporation comes from increased winter temperatures but also the change in timing of rainfall, with rain fall outside of the early to mid winter period tending to result in increased total evaporation (Ali et al. 2012).

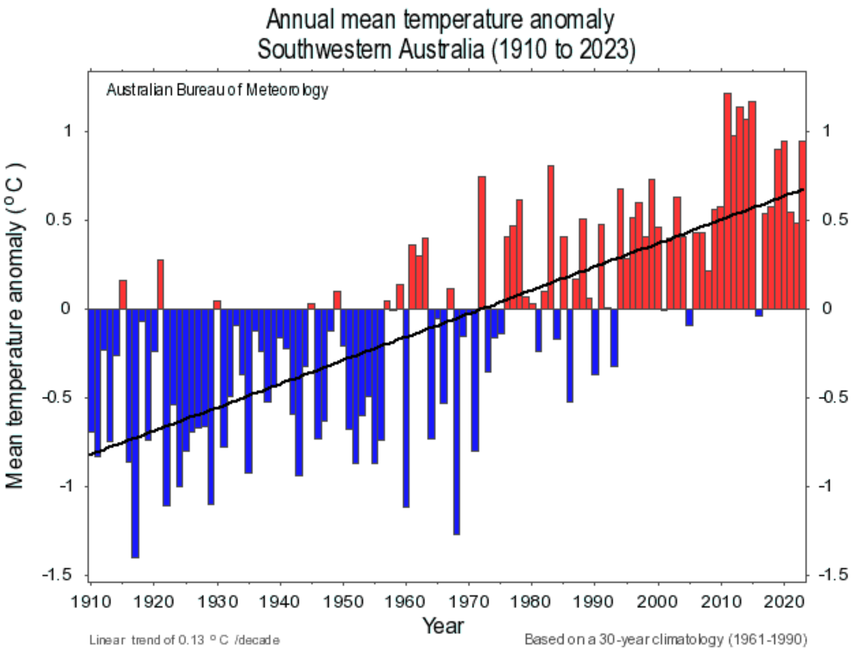

Figure 14 Annal mean temperature anomaly Southwestern Australia (1910-2023). Source [Australian Bureau of Meteorology](#).

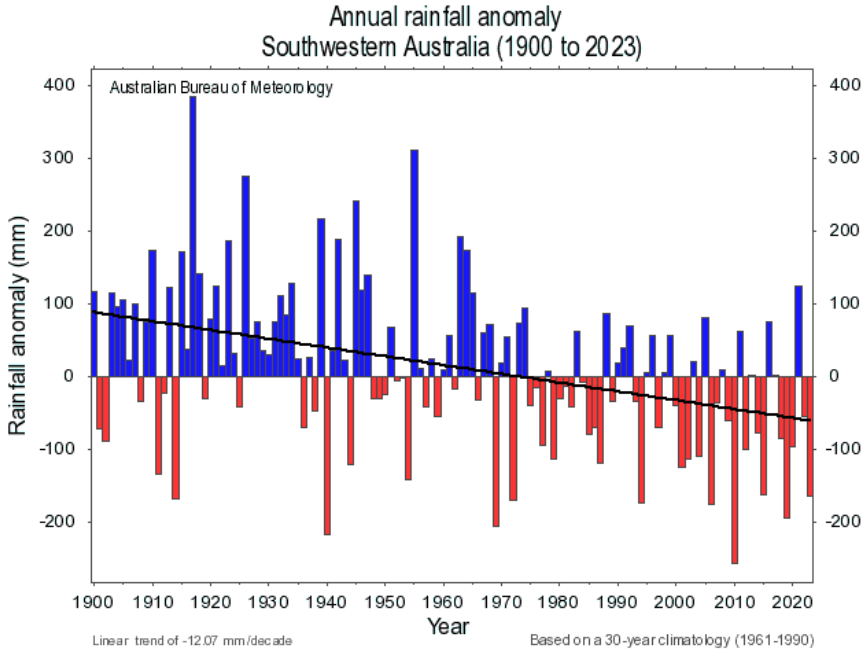

Figure 15 Annal mean rainfall anomaly Southwestern Australia (1910-2023). Source Australian Bureau of Meteorology.

Long-time series data

There is evidence the climate across the Western Bioregion has been warming and drying since as far back the late 1900's. The earliest climate dataset for the region (c. 1830-1875) suggests a period of relative stability in the mid to late 1800's (Gergis et al. 2021) and recent work by the Bureau of Meteorology has reconstructed a national time-series of temperature and rainfall from 1910 to present using standardised long-term weather stations across the country (Australian Bureau of Meteorology 2018). This dataset (known as the Australian Climate Observations Reference Network – Surface Air Temperature or ACORN-SAT) provides a useful resource to explore annual and seasonal trends by regions. Across the Southwestern region of Australia there is an adequate density of consistent temperature records from Geraldton to Albany to create a bioregion specific re-construction from the ACORN-SAT data (Australian Bureau of Meteorology 2018), which is broadly representative of the Western bioregion, including mid-west and metropolitan areas. For this Southwestern region, there is a clear trend of warmer annual temperatures (Figure 14) and decreased annual rain fall (Figure 15). The ACORN-SAT data is also accessible at a monthly temporal resolution and when restricted to winter months provides an even more consistent pattern of increasing temperatures (Figure 16) and decreasing rainfall (Figure 17) that for the annual averages. These warmer temperatures during winter are proposed to be a key factor in increasing evaporation and potentially decreasing ground water recharge (Ali et al. 2012).

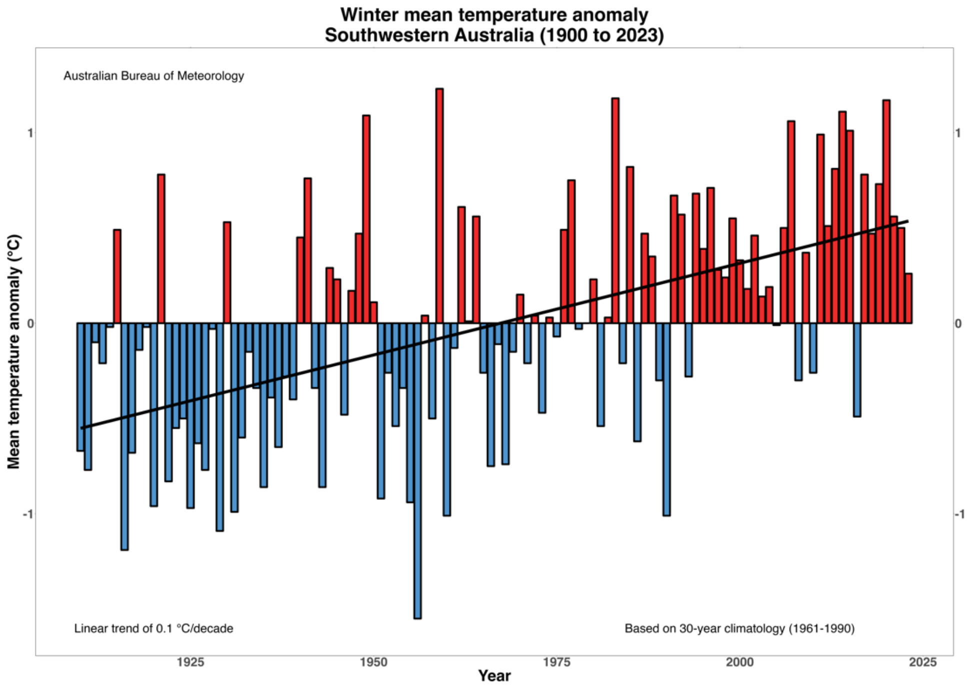

Figure 16 Winter mean temperature anomaly Southwestern Australia (1910-2023). Source [Australian Bureau of Meteorology](#).

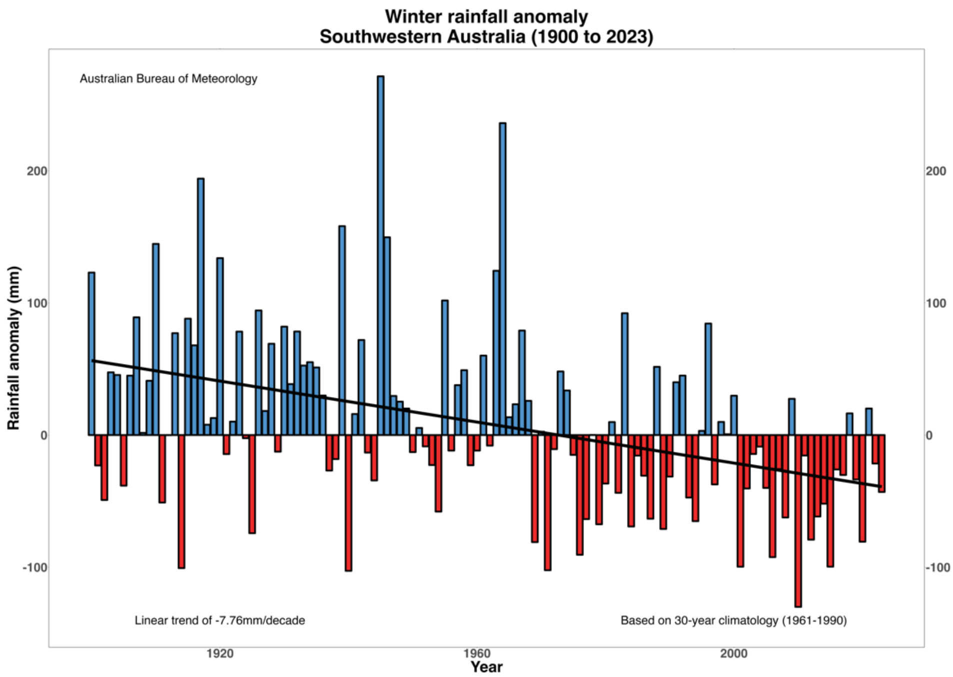

Figure 17 Winter mean rainfall anomaly Southwestern Australia (1910-2023). Source [Australian Bureau of Meteorology](#).

Ground water recharge

The pattern of a warming and drying winter is particularly relevant for ground water, as there is a close connection between the seasonal timing of rainfall, evaporation rates and groundwater recharge (Hughes, Petrone, and Silberstein 2012). In Southwestern Australia, Hughes et al. (2012) demonstrated that groundwater storage acts as the catchment's "memory", whereby years of lower winter rainfall during milder conditions of warmer winters with greater evaporation, can have lasting impacts on ground water hydrogeology. Recent research using indirect records from mineral deposits in caves, suggest that in response to the sustained decrease in rainfall across southwest Australia that began in the late 1960s, groundwater recharge may no longer be reliably occurring in this region, a situation unprecedented over the last 800 years (Priestley et al. 2023).

Given the strong evidence of increased winter temperatures and decreased winter rainfalls, it is highly likely that hydrogeological processes and SDG flows across the western bioregion have been impacted (Gergis et al. 2021).

Conclusion

Ecological processes within the shallow coastal systems and embayment's of the Western bioregion likely evolved with a different regime of SGD experienced today along this coast. We do know that SGD flows can deliver large volumes of low salinity and nutrient rich waters to these coastal areas and lagoons and suspect that changes in these flows will have impacted the species-specific growth of seagrass and macroalgal assemblages and potentially the animals associated with these habitats such as Wester Rock Lobster. The unique oceanography of mid-western and southwestern Australia, with the dominance of the Leeuwin Current suppressing upwelling along the coast (Pearce and Phillips 1994) also results in decreased mixing between offshore and nearshore coastal waters (Johannes et al. 1994), making productivity within these coastal waters potentially even more reliant on nutrient inputs from terrestrial surface or subterranean flows.

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