

Shifting the discharge mindset from harmful to habitat: exploring inventive designs and benefits of underwater discharge structures

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ABSTRACT

A zero discharge seawater desalination approach still appears to be very optimistic, especially when it comes to the large volumes of product water and associated brine (concentrate) that requires appropriate disposal. In addition to this, and although the technology advancements of mining for precious metals from brine show promising potential, it is still a challenge to use a single method to selectively extract valuable minerals from complex brine matrices. These two alternatives, (i) zero discharge and/or (ii) mining for minerals (from brine) may not be the best selections when designing underwater discharge structures (at least for the foreseeable future). With the aim to protect the marine environment, regulations have been set to regulate the brine discharges and defining environmental criteria in the area close to the outfall. It was however noted, that such criteria are often adopted from generic benchmarks and sometimes from unadoptable locations. Robust and *in situ* research on the effects of the brine effluent on the marine environment is also lacking. Recent surveys, however, suggest that the ecological impact of brine outfalls can be very limited or even result in an improvement of biodiversity and marine abundance on the outfall structure. Such observations suggest that some environmental criteria may be archaic, which may result in needlessly expensive outfall designs. Additionally, the hard substrate that the outfall structure provides appears to be a good habitat for the enhancement of marine growth. We therefore propose, instead of only aiming to minimize impact, also to promote the ecological habitat function by optimizing the design criteria of underwater discharge structures. Our paper presents first guidelines/examples (of shapes and material use (e.g., Coating with eco concrete)) to promote coral growth, nursery ground for fish, etc. Furthermore, we provide initial ideas for the treatment of the desalination effluent to help the advancement of such marine habitats.

Keywords: Desalination, Underwater discharge structures, Habitat, Environmental impact assessment, Mitigation, Building with nature

1. Introduction

Desalination plants do not only produce potable water, but also brine. A recent study estimates that the average desalination plant actually produced 1.5 times more brine than desalinated water – 50% more than previously thought.

The effects (or lack thereof) of desalination concentrate discharge have been discussed numerous times in literature and vary widely [1–4]. It is not only site-dependent, but also subject to the marine organisms around the discharge area (the biotic community), the nature/source of the effluent, and to what degree it is been disperse in the marine environment. From an environmental point of view, the design of the particular discharge structure must be adequate so that

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it ensures that the effluent stream that is discharged adheres to the receiving water guidelines (ambient standards). In addition, it also needs to ensure that environmental quality standard limits will not be exceeded at the boundary of the regulatory mixing zone (RMZ). On a global scale, only a limited amount of country-specific legislation and guidance addressing desalination-specific discharges, in particular, can be found. Many of the current regulations appear to be dated (in some cases almost irrelevant), and mainly copy-and-paste approaches issued by ad-hoc regulatory authorities [5].

Commonly, limits apply at the boundary of the RMZ, depending on the “significance” value and depth at the discharge area (normally to a maximum distance of 100 m). However, the habitual benefits of underwater discharge structures have often been overlooked, as a result of a predominant focus on the discharge limits (e.g., temperature and salinity) and regulatory compliance. Even though “desalination-developed”-countries have added regulatory standards for concentrate discharges into the marine environment (often even including requirements for the use of best available technologies), they are still lacking appropriate monitoring programs. Granting that desalination is not a new phenomenon as a source for potable water supply, it may be new to some countries that recently started to investigate the option to combat prolonged droughts and water scarcity. With this in mind, there is a high probability that a lack of guidance and/or guidelines may create insecurity for likely investors and also lead to unfounded concerns for those authorities responsible for issuing environmental regulations and permits, specific to desalination projects.

It is accepted that pre-treatment processes against fouling and/or corrosion may change the chemical composition of the receiving waters and could also result in eutrophication when phosphate-based antiscalants are used. This is due to oxidation or substitution reactions with organic and biological components. In a discharge area, this can result in the release of new nutrients in the local environment, which can (if managed adequately (in order to prevent algal blooms)) stimulate a variety of aquatic habitats. Numerous studies support the fact that various marine organisms have the ability to adjust to changing environmental conditions [6–12] and even benefit from an abundance of added nutrients. Discharging large volumes of cooling water may also introduce possible benefits specifically with regards to recirculation in areas of stagnant or low water flowing environments. The appropriate design of a discharge/outfall structure can possibly also provide an additional substrate that can enhance larval and coral fragment settlement to enhance reef restoration processes.

2. Environmental fundamentals

Environmental protection aspects are essential for the sustainable development of desalination projects. Most of the previously investigated environmental issues in literature are not exclusive to only a solitary desalination discharge and can, therefore, be made applicable to other facilities. The main differences are in the desalting process, the interpretation of regulatory requirements, environmental monitoring (or lack thereof), and impacts on the marine environment. Discharge volumes are expected to increase significantly over the

next decades as global water demand rapidly increases. Furthermore, environmental awareness and protection are also on most of the worthwhile governmental agendas and as a result of this, compensation projects (also known as environmental offsets) are more often included as a mitigation measure. There is certainly also evidence that the industry is required to invest in more hybrid desalination methods and technologies, this however, still requires a quantum leap in performance [13]. These trends provide interesting opportunities to combine the minimizing of outfall impacts with opportunities for innovative and sustainable designs of underwater discharge structures.

Albeit concentrate discharge is unlikely to alter the salt concentration of larger water bodies (even if they are somewhat enclosed). For example, the Mediterranean Sea or the Arabian Gulf, natural evaporation rates far exceed the concentrating influence than that of concentrate discharges. On a more local scale, however, the environmental impacts of the hypersaline discharge can be more problematic and can be attributed directly to a specific plant. The two major local environmental issues that arise from the desalination process typically originate from discharges of concentrate and chemicals as well as from considerable air pollution associated with power plants, which are necessary to drive the energy requirements of either thermal or membrane desalination processes. The latter issue can be minimized by employing renewable energy sources accompanied by a novel membrane and desalination technologies. However, the concentrate discharge remains a challenge.

3. A symbiotic methodology: bio-opportunity vs. environmental-impact

The viewpoint of this brief report is based on the recent Dutch approach to coastal works, that is, building with nature (BwN). The Netherlands has adopted a new and proactive style of developing extensive coastal (and river) works. Rather than simply minimizing and/or mitigating the environmental impact of a project, the idea is to make use of the dynamics of the natural environment and provide opportunities for natural bio-processes. The question, therefore, became apparent: “Why not also for underwater discharge structures?” We certainly can’t change ambient conditions, but together with selecting the most suitable discharge location, the required salinity reduction can be achieved through sufficient near field hydrodynamic mixing and appropriate discharge/outfall design. This BwN approach may contribute to shifting the “typical mindset” that discharges and associated structures are always detrimental to the environment. The traditional approach of typically focussing on minimizing the environmental and operational impacts only often overlooks the opportunities that could be associated with effluent discharges (dilution) and underwater structures (habitats).

3.1. Application of the BwN methodology to underwater discharge structures

The BwN concept is based on principles that encourage a sustainable, sometimes innovative approach, thereby often creating multi-functional solutions beneficial to multiple

stakeholders. It focuses on opportunities and win–win solutions, thereby thinking outside the box of limited, unfunctional problem perceptions and sector interests. This often requires evaluating the long-term costs and benefits of the different multi-functional alternatives. The objective is to align the interests of economic development and care for the environment – working with the natural system in such a way that the infrastructural needs and the interests of stakeholders are met, while new opportunities are created for the environment. This can often be achieved at lower costs on a life-cycle basis than projects based on the traditional approach. Instead of the traditional approach, which mainly focusses on minimizing or mitigating the impacts of the brine and associated underwater discharge structure, a more proactive approach is needed, which may result in the optimization of all functions and ecosystem services.

3.2. How can this be achieved?

The design process starts with a thorough understanding of the natural system, the desired function of the envisaged infrastructure and the vested interest of stakeholders. This is contrary to the traditional approach, which starts from a design concept focusing on the primary function. The following design steps (adopted from BwN) could be applied to the multi-use discharge design process:

- *Phase_1*: Understand the system (physical, bio-environment, ecosystem services, and governance)
 - Acquire a better understanding of the system in which the project is planned (from sources with in-depth knowledge of the physical systems (data, academia, local knowledge, etc.));
 - Propose user functions and eco-system services beyond those relevant to the primary objectives (e.g., an underwater discharge structure – when designed appropriately – can also function as habitat). The aim is to identify potential win – win solutions.
- *Phase_2*: Identify realistic/feasible alternatives that will benefit ecosystem services
 - Promote alternatives that provide a true win–win solutions providing services beyond mitigation and that make maximum use of the system’s environmental potential (enhancing sustainability);
 - Acquire academic experts, decision-makers, and stakeholders in the formulation of feasible and cost-effective alternatives.
- *Phase_3*: Assess the value of the alternatives (and pre-select the primary option)
 - Evaluate the integral qualities of the design alternatives with the aim to combine them into a single optimal solution;
 - Compare the BwN underwater structure alternatives to the more traditional design (creativity pays off);
 - Involve the stakeholders in the valuation and selection process.
- *Phase_4*: Elaborate and fine-tune the selected design option
 - Consider practical restrictions and adhere to the applicable governance context (requires the involvement of the stakeholders).

- *Phase_5*: Formulate the solution for implementation
 - Translate the solution into a feasible technical design (actually implement the proposed solution (expertise/knowledge, available materials, sustainability criteria, etc.));
 - This process is dynamic, almost by definition. Make sure the project takes this aspect into consideration (adaptive execution requires adaptive management).

The benefits of this underwater discharge design methodology may lead to added value for the stakeholders, which can lead to non-complicated permitting processes and likely societal support for such projects. It also has the potential for cost-saving on a life-cycle assessment (LCA) basis and creates the opportunity for underwater habitats, which may substitute environmental offsets as an added mitigation measure.

Current examples: Learning from Existing Underwater Discharges

3.3. The King Abdullah University of Science and Technology reverse osmosis desalination plant

The seawater reverse osmosis (SWRO) facility at the King Abdullah University of Science and Technology (KAUST) was designed to provide all potable water needs for the campus as well as the residential areas as part of the complex. The plant has a product-water capacity of 40,000 m³/d with an average raw water intake on the order of 55,920 m³/d with a recovery ratio of 37%, resulting in an average concentrate flow of 35,230 m³/d (August 2012) that is discharged to the sea [7,8]. The outfall (discharge structure) is located at 39°04.444 E, 22°17.780 N, and sits at a water depth of just below 18 m, approximately 2.8 km from the pump station (Fig. 1a). The concentrate is pumped through a 1,200 mm diameter pipeline to the offshore structure (Fig. 1b) where the concentrate is pushed up in a concrete riser and discharged horizontally through four discharge screens (1,800 mm × 1,000 mm) approximately 6 m above the seafloor.

Diving as a means of data/sample collection was selected to ensure exactness, robustness, and repeatability of underwater sampling processes. Three comprehensive studies have been conducted to assess the possible environmental impact of RO concentrate discharge on microbial abundance and coral (*Fungiidae*) resilience when exposed to elevated salinity levels as a result of concentrate discharge [7–9,14].

Although it is widely accepted that SWRO concentrate has the potential to cause significant impacts on the marine environment, little understanding is based on actual monitoring involving state-of-the-art procedures for environmental impact assessment. Almost none of what is reported in literature depicts possible impacts on microbial abundance or coral resilience (salinity) in the near-field areas of concentrate discharge. There has been a lot of recent focus on mass-bleaching events as the oceans absorb most of the excess heat from greenhouse gas emissions, leading to rising sea temperatures. The good news is that some new evidence suggests that corals may be becoming more tolerant, even of rising water temperatures [15].

The main findings of the KAUST SWRO plant investigations are summarized below:

Based on *in situ* sampling campaigns and up-to-date flow cytometry (FCM) analysis, it appears that the anticipated impacts on microbial abundance in the near-field area of the KAUST SWRO discharge zone were minor. The results of this effort distinctly showed a change in microbial abundance as

a function of distance away from the discharge structure. The authors also considered a possible negative correlation between conductivity (mS/cm) and FCM events/ μL as well as the effect of elevated conductivity levels on microbial abundance and viability – which lead to the hypothesis that the observed changes might be a result of normal dilution, where the concentrate (high conductivity; low microbial

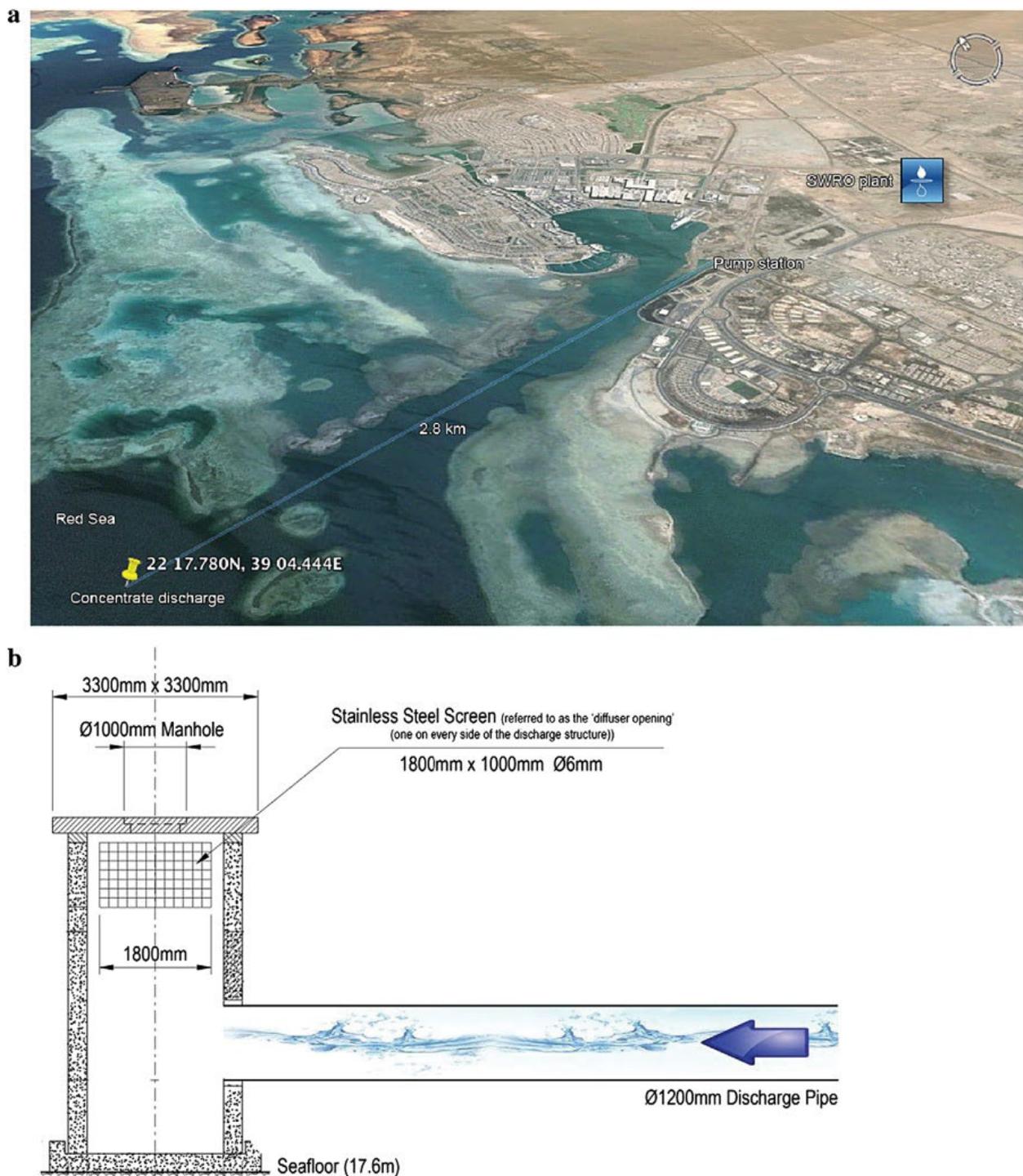


Fig. 1. (a) KAUST SWRO offshore discharge structure locality (source: Google Earth). (b) Schematic of the underwater discharge structure.

numbers) is “pushed” back into an already saline marine environment with preeminent bacterial abundance [7]. It was clear that the impact of increased salinity as a result of SWRO concentrate discharge is not limited to microorganisms, as this observation led to further research with a focus on an *in situ* coral photosynthetic yield experiment with the aim of assessing effects of higher salinity on coral photosynthesis in near-field areas of seawater desalination plants.

Coral health and survival largely depend on the interaction between the coral host and photosynthetic symbiont algae. In this study, the objective was to determine long-term effects (4 weeks) of a strong salinity increase on the coral *Fungia granulosa*. To do this, the authors transplanted corals along a 25 m transect away from the KAUST SWRO discharge structure, and determined salinity, temperature, oxygen, and light levels regularly. At the same time, they measured the (photo)physiological state of the algal symbiont via pulse-amplitude-modulation (PAM) fluorometry and checked for signs of visual bleaching. PAM fluorometry quantifies the photosynthetic efficiency with which light energy is converted into chemical energy at the photosystem II (PSII) level. Evaluating the chlorophyll fluorescence can indicate an organism’s photosynthetic efficiency under changing or stressful conditions, for example, varying salinity regimes. A video of the *in situ* work can be viewed here: photosynthetic yield experiment (DIVING-PAM) <https://vimeo.com/95486530>.

F. granulosa did not show any significant response to elevated salinities in this experiment. Directly at the discharge screen (as a worst-case scenario), corals were exposed to an average salinity of 49.11 g/L (9.51 g/L (24.01%) higher than ambient conditions) for a period of 29 d without any significant effect on photosynthetic performance [8,9]. Thus, within environmentally realistic salinity ranges to be expected as a result of SWRO concentrate discharge, it is expected that this species would be able to tolerate prolonged exposure to fairly large changes in salinity. Additional studies will be necessary to determine whether *F. granulosa* is unique in this regard and how other corals will respond to similar conditions. This could also suggest that some coral species contain mixed populations of zooxanthellae with different degrees of (salinity) tolerance; however, this speculation required further detailed investigation.

In conclusion, the studies conducted at the KAUST SWRO discharge showed evidence of rapid mixing of discharged brine with surrounding waters (even from a poorly designed underwater discharge structure with a very low exit velocity and little discharge-induced mixing) based on salinity and temperature measurements [14]. The results of changes in microbial abundance appear to be a result of normal dilution, where the concentrate (high conductivity; low microbial numbers) is “pushed” back into an already saline marine environment with preeminent bacterial abundance. The photophysiology of the coral *F. granulosa* exposed to the discharge environment along a 25 m transect was not influenced by rapid and prolonged changes in salinity (but varied according to changes in light conditions). The data further suggests that some coral holobionts might be remarkably resilient toward increased salinity levels, by acclimation to increased salinity levels in the concentrate discharge environment. Finally, the coral studies showed that cell cultures

of *Symbiodinium* only displayed inhibited cell growth at very high and low salinity levels. Based on this *in situ* experiment, it might be that some species possess a great acclimation potential to salinity changes, also in regard to discharge scenarios.

3.4. Perth seawater desalination plant

Like all desalination facilities, the concentrate discharge to the environment was raised as the main constraint for the development of this facility. It was perceived by some areas of the public and environmental bodies that the high salt content of the brine could impact the sensitive ecosystem of Cockburn Sound. The Perth seawater desalination plant (PSDP), with a production of 143,700 m³/d is able to produce 17% of the total potable water demand for the Perth integrated water supply system. The main areas of marine environmental concern were issues that relate to the dilution of the concentrate discharge, toxicity of the brine, and a perceived threat of dissolved oxygen levels.

An unprecedented marine monitoring program was called for as part of this project and included computer modeling for diffuser design and validation, rhodamine dye tracer tests, extensive far-field dissolved oxygen tests, a water quality monitoring program, diffuser performance monitoring program, whole effluent toxicity testing, and macrobenthic surveys. The monitoring methodology consisted of eight water quality sites and six transect sites which were sampled twice per season. The findings of the monitoring program support the findings of the modeling studies carried out during the development phase of the PSDP. In particular, the salinity impact was only evident on the eastern shelf of Cockburn Sound which was slightly higher than the ambient salinity of the receiving waters (up to 1 ppt at the seabed floor), however, all readings were well within the range of natural salinity variation (variable by up to 4 ppt seasonally). All other parameters showed no observable effect following the commissioning of the PSDP (except for total dissolved solids, which is closely linked to salinity). To meet the strict environmental requirements for discharge into Cockburn Sound, the seawater concentrate is returned from the PSDP 470 m into the ocean via a 40-port diffuser at the end of the discharge pipeline. The exit velocity is 4 m/s through nozzles spaced at 5 m intervals to ensure a total mixing of seawater concentrate within 50 m of each side of the pipeline. Instruments that continuously monitor plant discharges automatically shut down the process in the event of an exceedance.

All studies have proven that the PSDP is having a negligible impact on the surrounding environment and that impacts on seawater habitat are limited by a validated diffuser design and treatment of suspended solids [16].

3.5. Alicante desalination plant – echinoderms as indicators of brine impacts

Echinoderms are osmoconformer organisms and are expected to be very sensitive to brine discharges. These species may, therefore, be valuable as early indicators to monitor impacts associated with a desalination brine discharges, but also to detect a possible recovery of a previously impacted area when additional mitigation measures are implemented. During the first 2 y of operation of the Alicante desalination

plant, the authors observed the disappearance of echinoderms in the seagrass meadows directly in front of the brine discharge. As part of a follow-up study (for a period of 5 y), echinoderms appeared again at all the monitoring localities (0.04–0.08 individuals per m² (which is similar to prior commencement of brine discharge)) [17].

This is a good example of where a simple mitigation measure like diluting the brine with ambient seawater can again result in an increase of species abundance. Although the initial disappearance of echinoderms was described as a result of elevated salinity levels (pH, organic matter, and particle size composition of sediments were similar), it must be noted that these species can only tolerate a very narrow range of salinities. With this in mind, other more salinity tolerant species could have demonstrated none or very little effects as a result of the discharge. Further, this study was inconclusive whether the high(er) salinities produced an increment in the mortality of these species or induced its displacement to other areas outside the influence of the brine.

In total, the Alicante study areas have been monitored for 9 y (the facility has also been expanded during this period). The authors' observations confirmed the recuperation of the echinoderm densities where they have previously disappeared, mainly as a result of appropriate dilution. The study demonstrates that echinoderms can be good indicators of possible brine impacts (due to the species' salinity sensitivity) and may prevent damage to key ecosystems, for example, seagrasses.

3.6. Sydney desalination plant

This 7 y investigation describes the assessment of whether the discharge from the Sydney desalination plant (SDP) influenced fish assemblages associated with rocky reefs. This facility is a large-scale RO plant and has the capacity to produce up to 500,000 m³/d. Since 2010, the SDP has produced up to 303,000 m³/d of potable water, but the plant stopped producing freshwater in 2012 following the natural replenishment of Sydney's water storage dams. The plant remained mothballed until 2019 when it commenced operation. Fig. 2

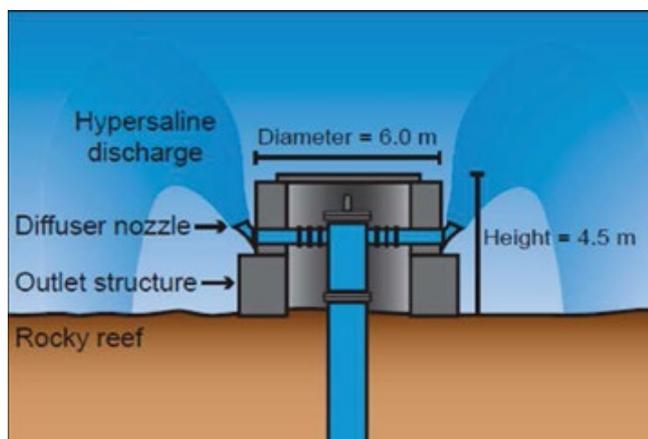


Fig. 2. Schematic diagram of one of four underwater discharge risers for the Sydney desalination plant. Source: Kelaher et al. [18] – effect of desalination discharge on the abundance and diversity of reef fishes.

shows the riser (one of four) that forms part of the underwater discharge structure for the SDP.

It is known that underwater structure (natural and/or artificial) in marine systems may enhance fish abundance. This case was unique, as it was not clear how the combination of enhanced habitat structure from the concrete underwater discharge structure itself and the associated discharge of hypersaline brine would influence reef fish assemblages. To address this, the authors tested the hypotheses that the operating desalination discharge outlet would impact reef fish community structure and diversity, species richness of fishes, and the abundances of fish with different functional traits.

The authors sampled reef fishes at two outlet sites and two close reference sites, as well as four reference sites that were located from 2 to 8 km from the discharge (12 times before, 8 times during, and 4 times following the cessation of discharging brine). Following the commencement of brine discharge, there was a 279% increase in the abundance of fish around the underwater discharge structure(s), which included substantially greater abundances of pelagic and demersal fish, as well as fishes targeted by recreational and commercial fishers. Following the cessation of brine discharge, abundances of fishes mostly returned to levels such that there was no longer a significant effect compared to the period prior to the commencement of the desalination plant's operations [18]. Overall, the results demonstrate that well-designed marine infrastructure and processes used to support the growing demand for potable water can also enhance local fish abundances and species richness.

4. First guidelines on ecologically friendly outfall structures

4.1. Importance of the associated underwater discharge structure(s)

These man-made underwater discharge structures could be seen as artificial reefs, typically built for the purpose of enhancing habitat, species abundance, and diversity. As the majority of discharge areas are desolate and sometimes featureless, these structures containing hard substrate can act as habitat on which soft and coral larvae can find surfaces to settle and it may also create shelter for fish and lower-order organisms. These structures can play a very important part in the ecosystem and the possible beneficial attributes of the effluent discharge are also often overlooked. If designed appropriately, it can benefit both regulatory hydrodynamic and environmental requirements with the aim to protect, enhance, and restore components of marine ecosystems. Owing to the environmental conditions under which these structures may function, it is important to guarantee proper maintenance and avoid any failure that might compromise the marine environment and lead to economic losses.

Saying this, with an adequate quantity of stable and durable substrate, man-made structures can be equally as productive in theory as naturally occurring hard-bottom habitats, limited only by the life-span of the materials used. There are many factors that can make an artificial reef a success or failure, and even the same techniques and materials

may work well in some situations and not in others. Many materials do exist that are effective, durable, and rather inexpensive, for example, concrete. It is a material that is very close in composition to natural coral limestone, and is also strong, heavy, cheap, and readily available all over the world. It can also be made into nearly any shape or size and is durable. Featureless debris, potentially toxic materials, and small/unsecured structures have been proven not to work. The focus should rather be on inventive designs that will fulfill in operational and regulatory criteria as well as resulting in ecological development.

4.2. Interaction of underwater discharges with ecology

Brine or thermal effluent from underwater (submerged) outfalls are typically discharged through a single pipe or multiport diffusers. The hydrodynamics and mixing behavior of the outfall plume can be distinguished in a near field, mid-field, and far-field domain. In the near-field, the motion is dominated by the momentum of the discharge and buoyancy induced by the difference in density of the fluid. The highly turbulent discharge interacts with the surrounding fluid. The flow around the outlet induces a circulation within it and the shear produces wave-like motions on the boundary of the rising plume, in the instance of a thermal effluent. In the mid-field, the plume spreads outwards and thins as it does so, the spreading even penetrating a short distance into the prevailing current. In the far-field, the velocity shear at the base of the plume will have become reduced to the extent that vertical turbulent mixing is minimal, and horizontal spreading and advection dominate.

The creation of a buoyant warmer plume (e.g. cooling water) will result in the fact that pelagic species, like fish, will stay closer to the coast and follow their normal swimming routes. Fish can detect the warmer water and will stay in the lower colder layers. In addition, any remaining biocides and their byproducts will stay in the warmer plume, and pelagic species are not exposed. Free residual chlorine and the main byproduct bromoform will decrease rapidly in a seawater plume due to photosynthetic reactions and evaporation into the air. For dense discharges, an analogy could be made near the bed.

To stimulate settlement of marine organisms in the outfall area it's important to take water velocities and turbulence into account. The role of local flow on settlement and recruitment of marine biofouling species is, however, still poorly understood. A study carried out by Pernet et al. [19] showed that the settlement success of the mussel species *Mytilus* spp., was positively correlated with centrifugal and advective flow velocity and turbulence measured immediately above the mesh bottom.

The availability of suitable substrate in an outfall area is important to stimulate marine species to settle and grow. Studies have examined the effects of surface topography on the settlement behavior [20] and it has also been observed that macro topographies (1–100 mm) are generally favored by marine fouling taxa and are unsuitable for antifouling applications. This is because macro topographies are usually large enough to fit fouling organisms and provide refuge from predation [21]. Earlier work from Berntsson et al. [22] showed that the barnacle, *Balanus improvisus*, prefer

settling on plain surfaces, whilst behavioral experiments confirmed that cyprids also have a higher propensity for smoother rather than micro-textured surfaces. Although some research has been done on the suitable substrate for biofouling organisms to settle, little is known about the effect of using different materials and structures to stimulate biofilm settlement with the aim of promoting diversity of species. In the Netherlands, research is carried out on different types of materials to use for coastal and river protection, for example, by creating artificial reefs in front of the coast. It was noted that sandstone rocks proved a very suitable material for settlement of species in comparison to the more smooth whin stone rocks (https://www.zeewerigenwiki.nl/wiki/index.php/PBZ_onderzoek_en_innovatie_Rijke_Dijken_VN). This will provide the basis for bacterial growth which stimulates the settlement and growth of other types of species like bryozoan, mollusks, tubular worms, tunicates, anemones, and other marine species. The availability of nutrients is not a limiting factor due to the continuous flow of seawater. Any effect of using biocides is very limited in the discharge, due to the fact that the concentrations are far below acute toxic levels. The impact is further reduced if the shape of the outfall stimulates a plume trajectory to reduce the mixing effect with the receiving seawater in the outfall area.

5. Discussion and outlook

We present an innovative approach to look at underwater discharge design by not only minimizing environmental impacts but by creating positive opportunities for marine environment and habitats. Built desalination outfalls in, for example, Saudi Arabia, Spain, and Australia have shown that negative effects on marine habitats were much lower than initially expected. Although the type and magnitude of impacts from discharges can depend on the specific desalting processes, studies shown that well designed marine infrastructure can result in habitat enhancement and that even large-scale desalination may not negatively affect particular species abundance (if appropriately managed and monitored). This calls for more research towards developing ecologically relevant and site-specific environmental criteria, to limit additional costs for outfall designs to comply with overly conservative environmental criteria.

Evidence exists that hard substrates in marine environments with otherwise mobile beds promote the growth of many different species. Some first relations have been found between the exterior material of structures and the promotion of growth of certain species, but much is still unknown. More research is therefore needed to develop guidelines for choice of outfall construction material and shapes to promote certain preferred habitats to develop.

The adoption of BwN design philosophy for underwater outfalls presents substantial opportunities to create added value for the stakeholders, which can lead to non-complicated permitting processes and likely societal support for such projects. It also has the potential for cost-saving on a LCA basis and creates the opportunity for underwater habitats, which may substitute environmental offsets as an added mitigation measure as part of desalination related developments.

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