Desalination 368 (2015) 3–9

Contents lists available at ScienceDirect

Desalination

journal homepage: www.elsevier.com/locate/desal

The use of simulated whole effluents in toxicity assessments: A review of case studies from reverse osmosis desalination plants

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HIGHLIGHTS

- Wastewater from desalination plants can impact the surrounding biota.
- Interactive effects may be identified by testing simulated whole effluents.
- We review three case studies in which simulated whole effluents were tested.
- Use of simulated effluents enabled various chemical combinations to be assessed.
- Drawbacks were consistent with assessments that use real effluents.

ARTICLE INFO

Article history:
Received 30 October 2014
Received in revised form 7 January 2015
Accepted 8 January 2015
Available online 20 January 2015

Keywords:
Brine
Environmental impact
Ecotoxicology
Marine
Wastewater

ABSTRACT

Seawater desalination is an increasingly common means to meet the demand for freshwater. Resulting wastewater discharges can, however, impact biota of the surrounding environment. Concern exists that interactive effects specific to the outputs of each desalination plant may result in unique impacts difficult to predict by studying existing plants or assessing the effects of individual chemicals found in waste streams. Given this, we highlight an alternative approach to assess potential toxicity of desalination outfalls. Specifically, we review three recent case studies from Australia in which simulated whole effluents were used in toxicity assessments before desalination plants were constructed. This approach enabled potential toxic effects of wastewater to be considered before the plants became operational and, in one case, even facilitated consideration of potential effects of different treatment processes and suppliers. As in many whole effluent toxicity assessments, the time required for testing and restricted range of species considered were limitations. Given the benefits of this method, however, the use of simulated whole effluents is a development that could facilitate an improved capacity to forecast impacts of proposed desalination plants.

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http://dx.doi.org/10.1016/j.desal.2015.01.014
0011-9164/

1. Introduction

Global population growth and associated patterns of consumption are placing increasing pressure upon resources, particularly freshwater [1]. Water scarcity is projected to worsen across much of the globe in the coming century, with severe shortages anticipated to affect 2.7 billion people in more than 80 countries [2]. Consequently, there is growing interest in methods to enhance the availability of freshwater. In coastal regions, desalination of seawater is increasingly explored and utilised as a method to complement other sources of water supply [3]. The process of desalination has a relatively long history in the Middle East (particularly the United Arab Emirates, Kuwait and Saudi Arabia), with capabilities rapidly expanding in the United States, Europe, China and Australia [3,4].

Desalination of seawater can, however, have environmental impacts, with particular concern often focussed on the potential effects of the resulting wastewater discharges returned to the marine environment. These discharges can have negative effects because of their highly saline nature, and also because they contain chemicals added during processing activities including chlorination, pH adjustment, coagulation, flocculation, dechlorination, antiscaling and membrane cleaning [3,5]. The resulting saline and chemical-rich waste streams can adversely affect surrounding environments by degrading water and sediment quality, impairing the functioning of marine life and disrupting the intactness of ecosystems (reviewed in [3,6,7]). Importantly, not only can individual contaminants (i.e., salinity or chemical additive) have a specific impact, but their effect may be exacerbated when added to the water column in combination, as occurs in the effluent from a desalination plant [8,9]. Thus, while some general conclusions can be drawn regarding the broad ecological effects of effluents, impacts may be relatively specific to each plant because the waste stream produced is dependent on the local seawater characteristics as well as the chemicals, processes and specific running conditions chosen for use.

The urgent need to obtain potable water in many parts of the world has meant that, historically (particularly before the 1970s), environmental issues associated with desalination had largely been overlooked or an issue of secondary concern [10,11]. Increasingly, however, the disposal of wastewaters is drawing attention both in terms of environmental approvals and public perception (i.e., obtaining a ‘social licence to operate’). This attention is particularly strong in developed nations such as Australia where environmental issues are often high on the public agenda and desalination is becoming more common [12,13]. Within Australia, desalination has the potential to provide an important source of potable water to growing coastal populations (~85% of the population lives within 50 km of the coast) and over the last few years a number of large (~50–200 GL a^{-1}) reverse osmosis plants have been built across the country to augment domestic water supplies of most of the major cities [12,14]. Perhaps less in the public eye, but equally important economically, is the production of water by desalination for industrial applications such as mining — to date industry applications have mainly involved saline groundwater, but increasingly seawater is being considered as a potential intake source and receiver of waste streams [12,15]. Ongoing uncertainty regarding the potential impacts of wastewater from desalination plants means, however, that limits of pollutants in wastewaters set by regulators in Australia are often highly precautionary, adding significantly to the cost of establishing and operating desalination plants. Consequently, a key issue is the development of a better understanding of the salinity and toxin tolerance of marine species in the vicinity of outflows [12], as this capability would likely bring both ecological and economic benefits.

Given concern regarding the potential impacts of waste streams, it is increasingly common for assessment of their toxicity to be conducted before a desalination plant becomes operational, and often before construction even begins. By conducting assessments early in the process, Australian regulators are able to assess the likely risks to the environment and, where deemed acceptable, to set licensing conditions (e.g., permissible waste stream volumes and concentrations) before any impact occurs. Complicating such testing, however, is the potential influence of local seawater characteristics, synergies among the specific chemicals released by each plant, and likely differing responses of the complex biota in the receiving environment [1]. One approach to this kind of assessment is to simply ignore the potential influence of synergistic effects — that is, to identify the potential effect of each contaminant that may be in an effluent and then add predicted responses to forecast the combined toxicity of waste streams. While such an approach takes into account local plant designs and likely running conditions, it cannot account for any interactive effects among the chemicals considered nor facilitate an understanding of the conditions which drive an interactive response [16]. An alternative approach is to conduct whole effluent toxicity (WET) assessments using wastewater collected from similar desalination plants that are already operational elsewhere. While this method addresses concerns regarding potential synergistic effects of multiple chemicals, the local context may be overlooked. That is, identifying similar plants can be difficult, with potential that the closest similar plant has differing seawater characteristics. Further, even where similar plants do exist within a suitable distance and samples can be obtained, information about associated running conditions and procedures may not be something the plant operators are willing to provide if this is outside of their normal licence conditions. Without such information, just how similar the actual (sampled) effluent under real running conditions is to that expected from the theoretical plants is difficult to gauge. In turn, this means that the results from WET testing may be hard to relate to the potential toxicological impacts of planned plant [8].

A need exists, therefore, for a way to consider the potential impacts of the whole (combined) effluents expected to be produced by proposed desalination plants which takes into account the specific characteristics of local environment, plant design and likely running conditions. An emerging way to do this is by WET testing of simulated whole effluent(s) manufactured to represent the outflow which will likely be produced by a specific plant under predicted running conditions. While this method holds promise and is increasingly utilised and advocated in literature resulting from applied studies (such as consultants reports and government documents, e.g., [17–19]), it has received relatively little attention in the academic literature and not, to our knowledge, been used widely outside of Australia. Here, our overall objective was to consider the potential utility of simulated whole effluents in toxicity assessments by reviewing three Australian case studies. Specifically, we consider the Cape Riche, Victoria and Gorgon reverse osmosis desalination plants. We have chosen this subset of Australian desalination plants as they provide a good indication of the various methods and approaches used in testing of simulated whole effluents (described below). In this review we summarise the background to each project, effluents simulated, models and hypotheses of interest, WET testing done, results (largely in terms of management applications), and assess any features of the assessments which constrained the efficacy of this approach.

2. Case studies

Simulated whole effluents are increasingly used in toxicity assessments conducted prior to and during the development of desalination plants. In a growing number of cases, reports summarising these assessments in terms of the specific approach used and results obtained are made freely available, which enables their comparison. Here, we review three such projects and their reports, specifically; the Cape Riche seawater desalination plant summarised in [5], the Victorian Desalination Project constructed in Wonthaggi as detailed in [20], and the Gorgon Development at Barrow Island documented in [8]. These reports form the basis of the following comparison(s), with detail included in this section obtained from them unless otherwise indicated.

2.1. Cape Riche seawater desalination plant, south Western Australia (Cape Riche) [5]

The Cape Riche Desalination Plant was proposed to be located in the South Coast region of Western Australia, approximately 90 km east north-east of Albany and 5 km west of Cape Riche [5,21]. The plant was to have the capacity to supply of 12 GL of treated water per year via pipeline to the Southdown Magnetite Project (an open pit magnetite mine) [5,21]. The desalinated water was to be primarily used as process water at the mine site, meeting 85% of make-up water requirements, with the potential for some to be further treated at the site and used as potable water if required. Following final environmental approvals for the desalination plant [21], however, plans for the mine were put on hold in November 2012.

For ecotoxicological assessment of the Cape Riche plant, a simulated effluent was created in the laboratory with chemical specifications matching those expected to be found in the wastewater from the proposed plant. The simulated effluent was produced by collecting seawater from near the expected site at Cape Riche and transporting it to a commercial ecotoxicology laboratory several hundred kilometres away in Perth. Once in the laboratory, the seawater was passed through a laboratory-scale reverse osmosis membrane to simulate the desalination process and then dosed with an antiscalant considered likely to be used in the planned plant; specifically, 'Nalco Permatreat PC-1020' [5]. Given that studies previously performed in Western Australia had identified elevated salinity and residual levels of antiscalant were of most significance when assessing the toxicity of desalination plant effluent discharges, it was considered important to assess a high salinity brine effluent including an anticipated residual concentration of antiscalant for testing [5] (Table 1). In Australia, environmental regulatory authorities usually adopt recommendations from ANZECC and ARMCANZ [22] and, where possible, assess potential environmental effects of chemical releases on ecosystems via WET testing on the widest range of (local) species possible, including representatives of different trophic levels [23]. Consequently, the toxicity of the Cape Riche simulated effluent was assessed for a range of marine organisms from six species considered representative of those found in the temperate waters of southern Western Australia where Cape Riche is located [5] (Table 2).

Table 2
Summary of the test species, and taxonomic groups they belong to, used in the Cape Riche, Victoria and Gorgon case studies.

Taxonomic group	Species	Cape Riche	Victoria	Gorgon
Microalgae	*Isochrysis galbana*	×		×
	Nitzschia colsterium		×	
Macroalgae	*Ecklonia radiata*	×		
	Hormosira banksii		×	
Annelid	*Diopatra dentata*			×
Echinoderm	*Heliocidaris erythrogramma*	×		
	Heliocidaris tuberculata		×	×
Mollusc	*Mytilis edulis*	×		
	Mimachlamys asperrima		×	
	Saccostrea glomerata			×
Crustacean	*Gladioferens imparipes*	×		
	Allorchestes compressa		×	
	Penaeus monodon			×
Fish	*Pagrus auratus*	×		
	Seriola lalandi	×	×	
	Lates calcarifer			×

The testing of six species allowed the calculation of a Species Sensitivity Distribution (SSD) for the simulated effluent, enabling predictions of the dilution factors necessary to achieve various levels of species protection if this effluent was to be released back into the waters near Cape Riche. Specifically, the chronic dilution factor calculated for the 99% level of species protection was 53 (Table 3); that is, testing predicted that effluent would need to be diluted 53-fold to result in a concentration such that 99% of species would not be expected to be affected by long term exposure. The dilution factors required to achieve (lower) protection levels of 95%, 90% and 80% of species were also reported and were 40, 35 and 28 respectively (Table 3). These dilution factors can be of use in two key ways. Firstly, from an engineering perspective, such information is important for designing adequate dispersion and mixing of effluents with receiving waters; e.g., ensuring systems have enough pressure, flow, and outfall nozzle jet dimensions to provide sufficient energy to get effective mixing that achieves the suggested rates of dilution quickly. Secondly, from the perspective of an environmental regulator, such information can be combined with modelled forecasts of the location, likely rates of mixing and areas of

Table 1
Summary of the simulated whole effluent treatments used in the Cape Riche, Victoria and Gorgon case studies.

Number	Treatment composition
Cape Riche	
1	Brine + antiscalant
Victoria	
1	Saline concentrate (brine) + antiscalant
2	Saline concentrate (brine) + antiscalant + membrane cleaning surfactant (worst case scenario)
3	Saline concentrate (brine) + antiscalant + membrane cleaning surfactant (worst case scenario) + biocide + prechlorinated
4	Saline concentrate (brine) + antiscalant + membrane cleaning surfactant (long term average) + prechlorinated
Gorgon[a]	
1	Brine only (no other additives)
2	Veolia brine effluent + backwash
3	Veolia brine effluent + backwash + CIP (variant i)
4	Veolia brine effluent + backwash + CIP (variant iv)
5	ITT brine effluent + backwash
6	ITT brine effluent + backwash + CIP (variant ii)
7	Osmoflo brine effluent + backwash
8	Osmoflo brine effluent + backwash + CIP (variant iii)
9	Osmoflo brine effluent + backwash + CIP (variant iv)
10	GE brine effluent + backwash
11	GE brine effluent + backwash + CIP (variant v)
12	Backwash only

[a] Note that for the Gorgon case study, each 'brine effluent' contains the relevant biocides, flocculants and antiscalants.

Table 3
Summary of the reported level of species protection (%), effluent (%) and safe dilution factor for the Cape Riche, Victoria and Gorgon case studies.

Sample code	Level of species protection (%)	Effluent (%)	Safe dilution factor
Cape Riche[a]		*Chronic*	
1	99	1.9	53
1	95	2.5	40
1	90	2.9	35
1	80	3.6	28
Victoria[b]		*Acute and chronic*	
1	99	3.2	31
2	99	6.9	14
3	99	5.2	19
4	99	7.0	14
Gorgon[c]		*Acute and chronic*	
All reported together[d]	99	10.3	9.7
	95	12.9	7.8
	90	14.1	7.1

[a] Reported here for Cape Riche are effluent (%) and safe dilution factors calculated using the EC10 values.
[b] Victoria case study combined EC10 and LC10 data using an acute to chronic ratio (ACR) of 2.5.
[c] Gorgon case study combined the EC10 and LC10 data using an ACR correction value of 2.
[d] 12 effluents were tested in the Gorgon case study, however, given that no effluent was found to be more toxic than the others individual effluent (%) and safe dilution factors were not reported.

Table 4
The alternative models and hypotheses that the Victoria and Gorgon case studies tested.

Case study[a] and option	Model	Hypothesis[b]
Victoria		
A	Additives exert acute toxicity	2 or 3 or 4 > 1
B	Additives do not exert any acute toxicity	2 = 3 = 4 = 1
C	Additives interact to decrease toxicity	2 or 3 or 4 < 1
Gorgon		
A	Brine per se is the most toxic component of the effluent and the presence or absence of flocculants, biocides and/or other backwashing or CIP components does not affect toxicity	1 = 2 = 3 = 4 = 5 = 6 = 7 = 8 = 9 = 10 = 11 > 12
B	Backwash is the most toxic component of effluent and the presence or absence of other components and/or brine does not affect toxicity	2 = 3 = 4 = 5 = 6 = 7 = 8 = 9 = 10 = 11 = 12 > 1
C	Backwash and brine is more toxic in combination than either alone and other components do not affect toxicity	2 = 3 = 4 = 5 = 6 = 7 = 8 = 9 = 10 = 11 > 1, 12
D	Certain supplier's effluents are more toxic than others, regardless of CIP chemicals used	2 = 3 = 4 And 5 = 6 And 7 = 8 = 9 And 10 = 11 And 2 > 1, 12 Or 5 > 1, 12 Or 7 > 1, 12 Or 10 > 1, 12 And not 2 = 3 = 4 = 5 = 6 = 7 = 8 = 9 = 10 = 11
E	CIP chemicals are the most toxic component, or make whole effluents more toxic, regardless of which CIP variant is used or supplier	3 = 4 = 6 = 8 = 9 = 11 > 1, 2, 5, 7, 10, 12
F	Some specific CIP variants are the most toxic or make a whole effluent more toxic, regardless of which supplier's treatment they are used with	3 > 1, 2, 4, 5, 6, 7, 8, 9, 10, 11, 12 Or 4 = 9 > 1, 2, 3, 5, 6, 7, 8, 10, 11, 12 Or 6 > 1, 2, 3, 4, 5, 7, 8, 9, 10, 11, 12 Or 8 > 1, 2, 3, 4, 5, 6, 7, 9, 10, 11, 12 Or 11 > 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 12
G	CIP chemicals are the most toxic component or make whole effluents more toxic, regardless of which CIP variant is used, but depending on which supplier's treatment they are used with	3 = 4 > 1, 2, 12 And 6 > 1, 5, 12 And 8 = 9 > 1, 7, 12 And 11 > 1, 10, 12 And not 3 = 4 = 5 = 8 = 9 = 11
H	Some CIP variants make a whole effluent more toxic, depending on which supplier's treatment they are combined with	3 > 1, 2, 4, 5, 6, 7, 8, 9, 10, 11, 12 Or 4 > 1, 2, 3, 5, 6, 7, 8, 9, 10, 11, 12 Or 6 > 1, 2, 3, 4, 5, 7, 8, 9, 10, 11, 12 Or 8 > 1, 2, 3, 4, 5, 6, 7, 9, 10, 11, 12 Or 10 > 1, 2, 3, 4, 5, 6, 7, 8, 9, 11, 12 Or 11 > 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 12

[a] No alternative models were assessed for Cape Riche given that only one simulated whole effluent was tested so this case study is excluded from the table.
[b] The effluents in the 'Hypothesis' are defined in Table 1 . In these hypotheses '1 > 2, 3' indicates that the toxicity of the whole effluent 1 will be greater than for whole effluent 2 and whole effluent 3 while '1 = 2' suggests that there will be no detectable difference in toxicity between whole effluents 1 and 2. Note that in bioassays the parameter chosen to measure 'toxicity' (e.g., LC10 or EC10) is measured as less when toxicity is greater.

increased concentrations to assess the potential for impacts on local ecosystems in terms of both severity and spatial extent.

The ecotoxicological assessment conducted for the Cape Riche desalination plant is a good example of how a simple approach of simulating effluents and using them in WET testing can provide information before plants are constructed, particularly where focus is placed on locally relevant species and receiving waters [24]. We note that while only one simulated effluent was tested, the number of species assessed (six) and logistics of using locally specific source water for creating test effluents still represents a substantial amount of work. We do highlight, however, that by using this simple approach the derived dilution factors are really only representative of a limited set of (idealised) running conditions—essentially those simulated. These simulated conditions may or may not produce the range of effluents resulting from the actual final plant, which would probably operate in varying and possibly unexpected conditions. For example, it is impossible to conclude the toxic effects that would result if a different antiscalant was used in the eventual plant and/or chemicals resulting from desalination processes were also included in the effluent streams (e.g., chemicals involved in chlorination, pH adjustment, coagulation, flocculation, dechlorination and membrane cleaning). Given this, the dilution factor may need to be modified under different running conditions not considered in this study. An additional limitation of testing just one simulated effluent is that the cause(s) of toxicity in the simulated effluent stream cannot be unravelled (i.e., a hypothesis considering the relative influence of brine vs. antiscalant vs. brine + antiscalant could not be tested). Accordingly, both of our other case studies involved more complex sets of treatments and tests.

2.2. Victorian Desalination Plant, Bass Coast (Victoria) [20]

The Victorian Desalination Plant was constructed in the south east of Australia, on the north coast of Bass Strait. The plant was designed to supply potable water to the supply system for the state capital of Melbourne (population ~ 4 million people) and possibly other regional supply systems [25]. Although the completed plant is now capable of supplying up to 150 GL of high quality drinking water each year, it has been placed in standby mode and will not be producing water for the short-term foreseeable future [26].

Before construction, WET testing was undertaken on potential effluents as part of the approval process for this plant, specifically EPA Works Approval Condition 2.3 and Performance Requirement PR217 [20,27]. Testing was done on four effluents simulated to encompass a range of operating conditions, specifically the long-term average outflow, worst case scenario within normal operating conditions, absolute worst case, and long-term average outflow composition together with cleaning in place (CIP) chemicals (Table 1). These effluents enabled consideration of models and hypotheses regarding different levels of production and some of the different processes involved in desalination (summarised in Table 4).

The four simulated effluents were produced using seawater obtained from near the location of the intake/outfall streams in Bass Straight (Wonthaggi) which was sent to a university based research centre in a different state (~1000 km away in Sydney, New South Wales) that specialises in reverse osmosis membrane desalination techniques. The water was pre-treated according to the requirements for each simulated effluent before being passed through a laboratory-scale reverse osmosis unit and processed until the required salinity was achieved. The processed brine was then used in testing conducted at a specialist ecotoxicology laboratory (also in Sydney, New South Wales). The tests were undertaken on six species found in the waters of Victoria or New South Wales with those from New South Wales closely related to species found in Victoria [27].

Similarly to the work done for Cape Riche, WET testing for the Victorian Desalination Plant was used to identify the safe dilution factors necessary for 99% (and other) level(s) of species protection. Here, this was determined for each of the four effluents separately, with the safe dilution factors ranging from 14 to 31 (Table 3). The ranking of the different effluents (as defined in Table 1) from most to least toxic based on safe dilution factors was 1, 3 and then equally 2 and 4. Interestingly, this result suggests that effluent 1 (which represents normal operating conditions) may be more toxic than those which represent the worst case scenarios or streams with additional chemicals (effluents 2, 3 and 4). Perhaps more importantly, the comparison of effluents did not suggest that the presence of biocide and/or surfactant in waste streams exacerbates the toxicity of the effluent, at least at the concentrations predicted. Although this approach required a lot (four times) more ecotoxicology work than an approach considering a single running condition, the obvious advantage is that it accounts for a wider range of operational conditions. That is, it was possible to consider effluents with different chemical constituents as could be produced as a result of varying running conditions and production schedules used over time, a reality in any operational desalination plant. Of course, as in the Cape Riche case study, the relevance of the results of WET testing is still related to how well the predicted (and tested) simulated effluents match the range of eventual effluents produced by the constructed plant.

2.3. Gorgon desalination plant, Barrow Island, Western Australia (Gorgon) [8]

The Gorgon desalination plant was constructed on Barrow Island, around 60 km off the northwest coast of Western Australia [28]. This desalination plant was required to provide water for the construction and maintenance of the Gorgon Liquid Natural Gas Development, a facility for processing and exporting liquefied natural gas (LNG) to international and domestic markets [28]. Given its offshore location, the continuous provision of locally produced freshwater was critical for the plant and exporting facility, during both the construction phase and ongoing operations. The remote nature of Barrow Island also meant that for logistic reasons all desalination waste would need to be released into the marine environment as effluent and as such needed to be assessed by local environmental regulatory authorities [8].

As with the other case studies, consultation with the relevant environmental regulatory authorities regarding marine waste discharges led to a recommendation for WET testing on simulated effluents to assess the potential toxicity of wastewater. Additionally, as for the Victorian plant, regulators were concerned with the potential for synergistic effects of combined waste streams incorporating effluent from brine production as well as periodic inputs from processes such as membrane cleaning and backwashing [8]. The Gorgon testing was, however, further complicated as at the time approvals were being sought a final decision had not yet been made about which of several alternative reverse osmosis systems might be employed. Each potential system used slightly different processing schedules and at least one unique chemical (i.e., proprietary to the supplier), complicating decisions regarding which simulated effluents should be considered in testing. In contrast to previous case studies outlined above, the effluents simulated and used in Gorgon WET testing were, therefore, selected not only to cover a number of operating processes ($n = 6$), but also a range of potential suppliers with unique chemicals/application rates ($n = 4$). This complexity led to the identification of 24 unique potential whole effluents that could be released and, ideally, needed to be assessed via WET testing. The approach taken to rationalise this large number of potential effluents was to test only a subset ($n = 10$, plus two control treatments) and look for evidence of differences in toxicity among these using relatively complex statistical approaches [8]. That is, 12 simulated effluents were considered which covered a range of suppliers and processes (summarised in Table 1) with the relative effects then used to examine a range of different hypotheses and models regarding relative toxicities and interactive effects (described in Table 4). If any evidence of synergistic toxicity was found further WET testing would then have been done on other (initially not-tested) combinations to resolve patterns of toxicity further. Ultimately though, this was not required because there was no evidence of any waste streams actually being more toxic than just the brine component [8].

Given the added complexity in experimental design associated with considering a greater number of treatments in this monitoring programme, it was necessary to simplify the methods used to simulate effluents and conduct testing in an established ecotoxicology laboratory capable of dealing with the large volume. As in the other case studies, effluents for the potential Gorgon plant were simulated taking into account local seawater composition at Barrow Island and calculations about likely dosing rates and frequencies of chemicals used during different processes; for Gorgon, however, this was repeated for each of the four suppliers. The simulated effluents were created using sea water collected from near Barrow Island which was shipped to the commercial ecotoxicology laboratory (based in Sydney, New South Wales). In the laboratory, brine was simulated by concentrating the sea water via evaporation rather than reverse osmosis, with the appropriate chemicals added to each effluent at modelled concentrations. Although the number of marine species (six) tested was similar to that used in other case studies, the species selected for the Gorgon study were those that could be tested reliably in the ecotoxicology laboratory, rather than organisms sourced specifically from Barrow Island. While the species tested were all relevant to Barrow Island (Barrow Island was within the distributional range of most of the species), two were close relatives of species found at Barrow Island rather than actually being found there (Table 2). Moreover, all of the test organisms were sourced from the wild or aquaculture near the (temperate) testing location in Sydney (1000 s of kilometres away from Barrow Island) and simulated effluent was diluted using water collected from the Sydney region.

Testing of the 12 simulated effluents failed to detect evidence that any were more toxic than others, and none of the eight proposed hypotheses regarding differences in toxicity of the effluents were supported. Rather, this testing revealed that the toxicity of simulated whole effluents composed of just brine or sodium hypochlorite in seawater was not detectable as different from those which contained additional chemicals that would be used during the pre-treatment, post-treatment or cleaning in place processes; i.e., there was no evidence of synergistic toxic effects. Given the similarity among effluents, a single PC99 and safe dilution factor were calculated, which indicates that a dilution factor of 9.7 would be appropriate (Table 3). In addition, the safe dilution factor was also calculated using an alternative and more conservative approach based on the minimum concentration of whole effluent where no biological effect was detected (NOEC) and the application of a safety factor of 10. As anticipated, this method indicated that a more conservative dilution factor of 40 should be sufficient to protect 99% of species.

3. Discussion

Desalination of seawater can alleviate water scarcity in coastal areas and provide benefits to human populations, yet this process may also negatively affect biota of receiving waters as it creates wastewater containing high levels of brine and chemical contaminants (reviewed in [3, 6]). Current techniques used to forecast the potential effects of wastewater discharged from proposed desalination plants are imperfect [29], but the use of simulated whole effluents in WET testing may allow improved predictions of toxicity. Here, we have reviewed three case studies (Cape Riche, Victoria, Gorgon) in which simulated whole effluents were used to estimate safe dilution levels of outflows before the plants were constructed (summarised in Table 3). In two of these case studies (i.e., Victoria, Gorgon), the testing of multiple simulated whole effluents also provided a way to assess the potential (relative) toxicity of different contaminants and waste streams and, in one case (i.e., Gorgon), this information was obtained even before the supplier of the desalination plant was selected [8,20]. Interestingly, where the relative toxicity of different effluent components was considered, salinity was identified as having the strongest influence, with a lack of interaction among contaminants (synergistic or otherwise) [8,20].

Central to the use of simulated whole effluents in testing for toxicity is an assumption that the effluent tested is similar to that which will be produced by an operational plant. As in the case studies considered here, efforts are made to maximise the similarities between the effluent simulated and actually produced. Given that the plants are not, however, producing or releasing effluents at the time of testing, approximations need to be made. Consequently, differences may result where desalination plant management is modified relative to that proposed before construction and/or operation (i.e., altered addition of cleaners, anti-scalants or other products) [30]. Additionally, although the effluents simulated, and tested, are often developed to mimic the long-term average outflow (i.e., the Cape Riche case study), it may be the pulsed addition of particular effluent combinations produced during shorter-term worst case scenario events that affect the biota more strongly. This potential was recognised in one of the case studies considered here, the Victorian Desalination Plant, where simulated effluents tested encompassed a range of operating conditions, specifically the long-term average outflow, worst case scenario within normal operating conditions, absolute worst case, and long-term average outflow composition together with cleaning in place (CIP) chemicals [20].

As the effluents used in testing are simulated, potential exists that methods used in their production may not necessarily produce effluent of the same condition as an actual, operational plant. Again, although efforts were made to mimic production methods, often these could not be identical to those used in a full-scale desalination plant. For example, to simulate saline brine in these case studies a variety of methods were used (i.e., passed through a laboratory-scale reverse osmosis membrane in Cape Riche and Victoria and evaporated in Gorgon; [20, 8,5] respectively), which may not modify the water column in the same way as reverse osmosis in an operational plant (i.e., RO can affect concentrations of some trace elements like Boron; [8]). Further, as testing was typically conducted at a relatively large distance from the location where the desalination plant would be located, further differences may result if the substances, and their concentrations within the wastewater, differ from that anticipated due to the natural composition of the treated water (i.e., phosphates, nitrates and ammonium) [30]. That is, while protocols typically specify that local receiving water is used as dilution water [24], this was not achieved in the Gorgon case study [8]. Whether this would make a difference to the toxicity of whole effluents is unclear, but at least some differences are known in brine that gets produced between the desalination processes and at different locations. These issues can, however, only be addressed when a real plant is running and water quality can be directly measured.

While there are some drawbacks associated with the use of simulated whole effluents in toxicity assessments, a key advantage is that they facilitate the consideration of various waste streams, potentially before the plant is constructed, enabling a better-informed decision making process. The complexity of alternative hypotheses and models that can be assessed using this method is only limited by the number and diversity of waste effluent streams that are simulated. Here, the case studies considered incorporated a range of simulated whole effluents (i.e., $n = 1$, 4 or 12) which enabled different complexities of models to be assessed, from the very simple (i.e., in Cape Riche the toxicity of a single effluent) to the complex (i.e., in Victoria and Gorgon the toxicity of specific combinations of chemicals likely in different processes and running conditions) (summarised in Table 4). Where the range of simulated whole effluents used to test hypotheses is narrow, this can result in greater uncertainty regarding which component of the effluent is driving the observed toxicity, leading to the establishment of conservative management targets. That is, in the case of Cape Riche the dilution factor was set to be that which reduced the level of all contaminants (including salinity) to levels below the recommended marine water quality guideline trigger values [5]. If testing had identified the influential component then management might have been subsequently developed to target that specific component, potentially resulting in more moderate targets.

While rigorous testing using multiple simulated effluents will likely be of benefit when it comes to establishing management targets, there are practical issues which may limit its implementation. That is, as the number of processes and potential suppliers considered in tested hypotheses increase, the possible combinations of chemicals expand drastically. The resources, particularly time, required to run assays using standard WET approaches mean that in many instances all of the identified combinations cannot be explicitly tested. This limitation was influential in the Gorgon case study in which, given the range of processes and potential suppliers considered, twenty-four whole effluents were identified that could have been tested [8]. In recognition of the difficulties associated with considering this number of effluents, the testing programme was designed to initially consider a representative subset of effluents (ten of the potential effluents plus two control treatments). If a result was found that supported multiple models or indicated the existence of interactive effects, additional assessments would have then been subsequently conducted [8]. Although this approach enabled a broad range of simulated effluents to be considered, potential remains that a particular effluent may, for some unanticipated reason, be more toxic than those that were tested, highlighting the need for development of a method that facilitates the consideration of more effluents.

A key aspect of effective WET testing is that it considers organisms living in the receiving environment likely to be impacted. For example, the use of appropriate (local) species is of particular interest and importance in Australian studies given its geologically long separation from most Northern Hemisphere continents [23]. Thus, it is interesting to note that the case studies considered here undertook testing on a similar suite of taxa (in some cases the same species), despite the fact that they were considering three geographically distant areas, on opposite sides of the continent, in both tropical and temperate zones (summarised in Table 2). Although recognised as important, ensuring testing uses organisms found in the receiving environment or are closely related to organisms that are is currently difficult given that most assays are highly technical, and so are often conducted offsite (described in [24]). The most striking example of this in our case studies was from Gorgon; while the anticipated impact site was located in northwest Western Australia, testing was conducted in Sydney, approximately 3750 km away. While it was recognised that sourcing test organisms from local populations near Barrow Island would have been the best option, this was not possible due to potential quality control issues associated with transportation of marine organisms from such a remote location to an ecotoxicological laboratory in a capital city. The organisms chosen, therefore, were those which could be sourced near the testing location in Sydney, where the ecotoxicology laboratory contracted to do the work was based [8]. Further, given the complexity of tests conducted, the organisms ultimately selected were those that the ecotoxicology company had a large amount of experience working with, both in terms of husbandry and quality assurance tests [8]. This is particularly important given that key biota in particular areas, potentially including those for which ecotoxicological tests have not been developed, could be more sensitive to contaminants than those species typically considered [24,29]. Consequently, estimates may be improved if methods were used which enabled consideration of a greater diversity of species, including those of the environment likely to be impacted, as may occur if the method could be implemented outside of traditional WET testing facilities.

4. Conclusions

As desalination is increasingly used to alleviate water scarcity, potential exists that this process may impact marine environments. Consequently, new approaches for identifying potential effects and enabling their mitigation are likely to be increasingly desirable. The use of simulated whole effluents allows a variety of hypotheses and models specific to the contaminants and area of interest to be directly assessed, an outcome not possible if using the more traditional methods of forecasting likely impacts of desalination effluent disposal (e.g., considering the impacts of currently active plants located elsewhere or identifying the effects of multiple effluent contaminants separately). While representing an improvement in impact assessments of plants before their construction, our review highlights that these tests remain imperfect with issues largely linked to the WET methods used, specifically the time these tests take to conduct and limited species which can be considered. If the methods applied in such testing continue to improve we anticipate that over time the use of simulated effluents in WET testing will increase. This method could facilitate site-specific investigations and the derivation of relevant local management targets across a wide range of geographic areas for different desalination plants and processes, potentially well before plants are constructed. Given these potential benefits, testing using simulated whole effluents could become an integral component of regulatory approval mechanisms.

Acknowledgements

This paper was possible because the companies responsible for the monitoring programmes outlined have made detailed information freely available on the internet, which we gratefully acknowledge. We also acknowledge the comments from an anonymous reviewer. Funds provided to UCL by BHP Billiton Sustainable Communities supported LJF.

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