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Assessing the vulnerability of Dutch water bodies to exotic species: A new methodology

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Abstract Invasive exotic (alien) species have not been taken into enough consideration concerning the European Water Framework Directive (WFD) and other European directives until recently. The Dutch ministry responsible for water management is looking for ways to establish the impacts that invasive alien species may have on specified water types. This paper concentrates on the vulnerability of such water types to the introduction of exotic species. This new approach focusses on the system where the alien species are introduced into rather than only on the alien species themselves. We propose an equation that combines threats to and in water types with effects of particular species (observed or prognosticated). Numerical values used in the formula have been found by scoring a number of properties in different water types and species, which are specified in questionnaires. The results of the calculations are given as relative vulnerability scores (scale 1–10). By testing as many as 8 water types and 13 species, we demonstrate that this method is flexible and easy to use for water managers. Our results can be translated into classes of vulnerability, which are represented on geographical maps with colour codes to indicate different degrees of vulnerability in the different water bodies. This readily corresponds to the way countries are required to report to the European Union in the context of the WFD. The method can also be generalized using functional groups of (exotic) species instead of particular species [*Current Zoology* 57 (6): 863–873, 2011].

Keywords Exotic species, Risk analysis, Vulnerability, Methodology, European Water Framework Directive, Water types

The number of non-indigenous species introduced to the Dutch surface waters has increased considerably in recent years (e.g. Bij de Vaate, 2004[1]; Van der Velde et al., 2002; Van der Weijden et al., 2007; Wolff, 2005). Such non-indigenous organisms, also called exotics, can have various impacts on the functions of a water body. They may threaten the biodiversity or food web structure, which in turn may concern public health, safety, and the economic functions of the water bodies. To be able to effectively manage exotic species, it is important for water managers to have sufficient knowledge about the origin, biology and ecology of the species. Such knowledge is necessary to be able to assess whether or not water bodies comply with the ecological demands (habitat demands) of the introduced species. It must also be established what kind of abiotic and biotic circumstances are present in the species' area of origin, because this is often not completely known. This may be a tedious procedure, as relevant data and literature sources are often difficult to access or find.

In 2008, the Dutch ministry responsible for water management proposed that exotic species have not been taken into enough consideration concerning their aim to establish the purposes of the European Water Framework Directive (WFD). The Netherlands among other European countries has defined water types for the WFD (Devlin et al., 2009; Rogers et al., 2003[2]). The purpose of the WFD is to attain and maintain a good ecological quality in these water types. The possibility of attaining and maintaining a good ecological quality depends on the available adjustable environmental parameters ('steering variables'), including chemistry,

[1] Bij de Vaate A, 2004. Invasive aquatic exotics. Background Paper for Management Paper Invasive Exotics of Dutch Ministy of Agriculture and Nature, The Hague (in Dutch).

[2] Rogers S, Allen J, Balson P, Boyle R, Burden D et al., 2003. Typology for the Transitional and Coastal Waters for UK and Ireland (Contractors: Aqua-fact International Services Ltd, BGS, CEFAS, IECS, JNCC). Funded by Scotland and Northern Ireland Forum for Environmental Research, Edinburgh and Environment Agency of England and Wales. SNIFFER Contract ref: WFD07 (230/8030): 146 pp.

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hydrology and morphology. A factor determining good ecological quality and functioning of the ecosystem is high biodiversity. Intruding exotic species can greatly influence these factors (Vila et al., 2010). A species such as the colonial seasquirt *Didemnum vexillum* could put great stress on the biodiversity in an area by covering many square kilometres of sea floor and overgrowing other indigenous species (Gittenberger, 2007; Stefaniak et al., 2009). Exotic species can also hamper functions of water bodies that are important for humans, including shipping, drinking water production, recreation, public health, and various industrial functions. The Pacific oyster *Crassostrea gigas* is an example of these species. It changes ecosystems, and can damage the hulls of boats, slowing them down and greatly hampering recreation. Swimmers and surfers also tend to cut their feet on the sharp edges of these oysters (Miossec et al., 2009). Exotic species can damage dykes, sluices, docks and harbour works. The shipworm *Teredo navalis* and the Chinese mitten crab *Eriocheir sinensis* are examples of such exotic species that have caused great damage to dykes (Epifanio, 2009; Wolff, 2005).

For these reasons diminishing the negative impacts of exotic species is a goal that fits well into the broad objective of the WFD and other European directives. It is thus important to be able to estimate how vulnerable water bodies are to exotic species. This is true for specific exotic species, but also for exotic species in general. The vulnerability of water bodies to exotic species is one of the factors determining the ecological quality of those water bodies, and is a factor to be taken into account in reports within the framework of various European directives. This insight has lead to a recent increase in the number of studies constructing a basis for risk analyses to be used in the context of the WFD (Arbačiauskas et al., 2008; Cardoso and Free, 2008; MacNeil et al., 2009; Orendt et al., 2010; Panov et al., 2009).

In the pursuit of the same goal, the Dutch ministry for water management issued the development of a method that can distinguish several levels of vulnerability of Dutch waters concerning the impact of exotic species. These identified levels may then be used to better achieve the quality goals for the European directives, including the Framework Directive for Marine Strategy (FDMS), Birds and Habitats Directives (BHD) and Natura2000. Using this methodology should facilitate quick establishment of the vulnerability of water bodies concerning the impact of exotic species even when the user does not possess sufficient relevant knowledge.

The method can be used as a starting point in setting up an early warning system for exotic species and their impacts on water bodies, which may enable a manager to act before an invasive species in a water body reaches its exponential increase phase. In most cases a successful establishment of an invasive species must follow three phases (Crooks et al., 2005; Van der Weijden et al., 2007): (1) *the introduction /first phase of establishment*: The species is introduced into an area for the first time and establishes itself as a small and often unobtrusive population. Sometimes this is immediately followed by a considerable increase in the population, but more often this next phase follows: (2) the *"lag-phase*". This is the period of time between the species' introduction to the area until the moment (often many years later) that the population starts to increase exponentially where the invasive species is present only as a small and unobtrusive population. In a stable water body an invasive species can maintain itself solely as a small population longer than it could in an unstable water body. (3) *The exponential increase* is the final phase where the population of the species increases exponentially and suddenly. This happens usually immediately after an unusually large fluctuation or disaster, such as an extremely cold winter that killed many of the indigenous species in the area. This would consequently decrease the threat of predators to the invasive species, allowing it to then quickly expand its populations, using the niches that have become empty. After an invasive species has established itself in a stable ecosystem, it can thus maintain itself better than in an instable ecosystem. An example of this scenario in Dutch marine waters is the tunicate *Didemnum vexillum*, which has invaded temperate regions from New Zealand to North America and Europe (Stefaniak et al., 2009). This species has already been present in The Netherlands since 1991, but only recently started to increase exponentially - particularly in the Oosterschelde (= relatively stable water body) and Lake Grevelingen. This occurred after the very cold winter of 1995–1996, which had decimated the populations of many indigenous species in the areas (Gittenberger, 2007). It has also recently been introduced in the Wadden Sea (Gittenberger et al., 2010), where it is still in the introduction/first phase of establishment. This tunicate was also found on the floating docks in a pleasure craft harbor, indicating that hull fouling may have been the import vector (Gittenberger et al., 2010). Another example of a species that has followed the three phases of invasive establishment in a water body, is the Japanese oyster *Crassostrea gigas*. It was introduced in the Netherlands under the assumption that it could not reproduce because the waters are too cold. This assumption at first seemed correct, but after a lag phase of about ten to twenty years the species suddenly was able to reproduce and went into the exponential increase phase (Wolff, 2005).

When developing the calculation methodology for vulnerability of water bodies to exotic species, various similar models used in other countries were used as a baseline. Many of these models have been proposed to estimate the invasibility (= vulnerability to invasions) of ecosystems. They are based on a number of different presumptions. Besides the model based on the (supposedly negative) relationship between species richness and invasibility, resistance against invasions has also been used as a basis for a model (Moyle and Light, 1996). The notion that either natural or anthropogenic disturbance has also been proposed to be the most important steering factor, as well as fluctuations in food and other resources (Davis et al., 2000). Repeated invasions of various species would be able to reinforce each other, i.e. the invasion-meltdown model (Simberloff and Von Holle, 1999), causing the invasibility to rise with increasing species richness (Bruno et al, 2003; Simberloff and Von Holle, 1999). A striking number of these theories appear to have originated from research on plant communities, some of which are discussed by Van der Velde et al. (2006). Van der Weijden et al. (2007) discuss the factors that cause a system to become vulnerable and what species, either native or non-native, are vulnerable. They also investigate the factors that cause species to become invasive, and which factors may be responsible for the fact that more invasive species originate from some areas than from others.

When a system is young (geologically speaking) there are most likely many unused niches available, increasing the vulnerability of the system to invasions (see e.g. Wolff, 2005). On a smaller time scale, niches often become available on a temporary basis due to disturbances, which can also allow invasions to take place.

Invasibility is really mostly determined by a combination of many of these factors. The scale of observation also makes a difference in the result.

There is also the “key-lock approach”. This approach indicates that the properties of an ecosystem –particularly the characteristics and ranges of the properties of the niches present – are important for an invasive species. It suggests that the invading species needs to possess the right properties to fit into the system (Heger and Trepl, 2003). It seems trivial, but can be an excellent basis for risk analyses, supposing it is possible to establish the properties and ranges required.

It is surprising that most of the risk analysis methods used for exotic species are based solely on the possible impact of the species, neglecting certain uses and characters that increase the vulnerability of an area to exotic species in general. Taking the excellent biopollution index proposed by Olenin et al. (2007) as an example, it is completely focused on the impacts of alien species on native species, communities, habitats and ecosystem functioning. It does not incorporate aspects including the use of an area for drinking water or the occurrence of rare species, which are threatened in an area and are therefore making the area more vulnerable, regardless of the impact that one or more specific alien species have on that area at the moment of the assessment. The approach to assess the vulnerability of an area proposed in our paper takes the impact of alien species into consideration similarly to Olenin et al. (2007), and combines this with aspects that threaten an area and aspects that are threatened in an area. The vulnerability of areas to exotic species in general depends on a number of properties of those areas, including the measure of isolation (connectivity), species richness, spatial and temporal variation in environmental circumstances, and measure of disturbance. The scale of the study is important. For a more precise analysis of the vulnerability, it is necessary to clarify the specific reactions of the system to the introduction of one or more exotic species, if possible with various properties and demands. That is the purpose of the methodology proposed here.

1 Materials and Methods

1.1 Methodology development

The methodology that was developed was based on the assumption that the vulnerability of a water body depends on:

A. the total number of threats on the concerned water body, divided into two categories:

B. what is the sensitivity of threats caused by the properties of the water body itself and the way it is used by humans;

C. which are the elements of the water body that are (can be) threatened (impacted);

D. the total potential effect of an exotic species on the concerned water body.

The method was then generalized by using the same set of properties for each observed water body, and the same set of characteristics of each exotic species.

1.2 Methodology validation

The developed methodology has been tested on eight water bodies. These water bodies are of different water types, which were conceptually exposed to thirteen exotic species. The water bodies and exotic species were selected in a workshop by a team of Dutch experts. This selection was made in such a way to best represent situations in fresh, brackish and marine waters. The selected water bodies are shown in Table 1, togerher with their WFD type. The selected species are: six fresh water species, floating marshpennywort *Hydrocotyle ranunculoides*, Quagga mussel *Dreissena rostriformis bugensis*, Ponto-Caspian amphipod *Dikerogammarus villosus*, red swamp crawfish *Procambarus clarkii*, Asp *Aspius aspius* and red cheek turtle *Trachemys scripta elegans*; five marine species: American oyster drill *Urosalpinx cinerea*, American warty lobed comb jelly *Mnemiopsis leidyi*, Asian shore crab *Hemigrapsus sanguineus*, Mystery colonial sea-squirt *Didemnum vexillum* and Japanese oyster *Crassostrea giga*); and two brackish water species: false dark mussel *Mytilopsis leucophaeata* and Atlantic croaker *Micropogonias undulates*.

1.3 Definitions

The definitions that were used in the present study are the following.

An *exotic species* is a species not originally occurring in our country (or in our ecozone) *and* can only reach our country from its area of origin through human aid, or has recently done so in this way. An *invasive exotic species* is an exotic species that can establish itself here or has recently done so, *and* can strongly increase its numbers *and* has a negative impact on the indigenous biodiversity, and/or the public health, and/or the safety, and/or causes economical damage (Plantenziektenkundige Dienst, 2007[3]). *Vulnerability* in this report is defined as the measure in which a water body is sensitive towards the establishment of invasive exotic species. This sensitivity is dependent on (1) aspects that threaten an area, (2) aspects that are threatened in an area, and (3) on the effect that one or more alien species may have on that area. Vulnerability is defined broadly because we hypothesize that all these aspects should be assessed to get a reliable measure.

2 Results

2.1 Vulnerability equation

The vulnerability of an area generally depends on the properties of an area and the way it is used by men, as well as the aspects within the area that may be threatened. The vulnerability of a water body to exotic species further depends on the effects that those species may exert onto the water body. The expression below combines these threats and effects, and leads to a relative value of the vulnerability of a water body to exotic species. The equation used for calculating the vulnerability of water bodies is:

$$\mathbf{V = (T+ E)/2}$$

V = the vulnerability of a water body to non-native species, giving an indication of how easy exotic species are introduced into the area combined with the severity of the problems that they can cause.

T = the total number of threats of a water body (or water type), divided into “what can threaten the water body”(e.g. pollution, import vectors, number of non-native species already present in the area), and “what can be threatened in the area” (e.g. tourists, drinking water extraction plants, endemic species).

Table 1 Water bodies selected to test the proposed vulnerability equation

Water body	Water type
1. Westerschelde (western part)	K3: Marine, open North Sea water
2. Oosterschelde	K2: Marine, open North Sea water
3. Eemshaven	K3: Marine, small harbor
4. Noordzeekanaal	Overg1: Brackish water, semi-stagnant
5. Biesbosch	R8: Fresh water, tidal changes, sand/clay bottom
6. Waal	R16: Fresh water, continuous current
7. Loosdrechtse plassen	M27: Fresh water, semi-stagnant
8. IJsselmeer	M21: Large freshwater lake

[3] Plantenziektenkundige Dienst, 2007. Report of Advisory Committee for Co-ordinating Agency Invasive Exotics (COIE).Commissioned by Direction Nature of Ministry for Agriculture and Nature, PD, Wageningen (in Dutch).

E = the effect a non-native species or group of species can have. **E** is split into habitat-suitability **H**, damage done in other areas **D**, and potential damage **P**.

The parameters V, T, and E can have a minimum value of 0 and a maximum value of 10. A V value of 0 means that the water body in not vulnerable towards a non-native species. Regardless of the E(ffect) a non-native species can have on a water body, i.e. E=0–10, if a water body is not threatened in the first place, i.e. T = 0, the water body is not vulnerable, i.e. V=0. Similarly, regardless of the amount of threats in an water body, i.e. T=1-10, if the non-native species has no effect, i.e. E = 0, the water body is not vulnerable, i.e. V=0. The equation V = (T+E)/2 should thus only be used when both T and E are more than 0. If either or both are 0, V = 0. The highest vulnerability value, i.e. V=10, accounts only for a water body that is extremely vulnerable, i.e. is very heavily threatened, i.e. T=10, where the invasive species is expected to have an extremely negative effect, i.e. E=10. The *Vulnerability* of a water body for a certain non-native species or species group is thus calculated based on the *Threats* in a water body, and the *Effects* of the non-native species / species-group on that water body.

To calculate *Vulnerability*, the parameters *Threats* and *Effects* have to first be determined. This is done respectively on the basis of a questionnaire for *Threats* (Table 2) and *Effects* (Table 3). In these questionnaires water types are repeatedly used as they provide information about the water bodies whose vulnerability

Table 2 Questionnaire for calculating the Threats of a water body

Threats total = $T_1 + T_2 + T_3 + T_4 + T_5 + T_6 + T_7 + T_8 + T_9 + T_{10}$		
T_1–T_5: What threatens a water body?		
T_1	Industrial water disposal, e.g. cooling water, eutrophication, etc.	
	No industrial water disposal	*Threats* = 0.0
	Some industrial water disposal	*Threats* = 0.5
	Much industrial water disposal	*Threats* = 1.0
T_2	Connectivity to areas with exotic species	
	No import vector present	*Threats* = 0.0
	Some import vectors present	*Threats* = 0.5
	Many import vectors present	*Threats* = 1.0
T_3	Natural biodiversity disturbing factors, e.g. seasonal variations in temperature and/or salinity	
	Water type = M7,19–21,29; R2,7,15,16; Kust3,4	*Threats* = 0.0
	Water type = M1,3,5,6,8,10,14–18,23–24,27–28,30–32; R4–6,8–14,17,18; Overg1,2; Kust1, 2	*Threats* = 0.5
	Water type = M2,4,9,11–13,22,25, 26;R1,3	*Threats* = 1.0
T_4	Buffer function, i.e. size of the water body	
	Water type = M15,21; R6–8,15,16; Kust	*Threats* = 0.0
	Water type = M5,7,10,14,19, 20,23,27,29–32; 2,5,10,12,14,18;Overg1,2; Kust1,2	*Threats* = 0.5
	Water type = M2,4,9,11–13,22,25, 26;R1,3	*Threats* = 1.0
T_5	Diversity of exotic species	
	Number of exotic species = ~5	*Threats* = 0.0
	Number of exotic species = ~10	*Threats* = 0.5
	Number of exotic species > ~20	*Threats* = 1.0
T_6–T_{10}: What is threatened in a water body?		
T_6	Diversity of native species	
	Number of native species = ~ 10	*Threats* = 0.0
	Number of native species = ~ 50	*Threats* = 0.5
	Number of native species > ~ 100	*Threats* = 1.0
T_7	Diversity of rare and/or endemic species	
	Number of rare and/or endemic species = ~ 0	*Threats* = 0.0
	Number of rare and/or endemic species = ~ 2	*Threats* = 0.5
	Number of rare and/or endemic species > ~ 4	*Threats* = 1.0
T_8	Habitat-variability, i.e. variation in salinity, currents and substrate	
	Substantial variation in 0 or 1 of these 3 parameters	*Threats* = 0.0
	Substantial variation in 2 of these 3 parameters	*Threats* = 0.5
	Substantial variation in 3 of these 3 parameters	*Threats* = 1.0
T_9	Recreational use, like surfing, swimming, scuba-diving, fishing, etc.	
	No recreational use	*Threats* = 0.0
	Some recreational use	*Threats* = 0.5
	Much recreational use	*Threats* = 1.0
T_{10}	Industrial use outer water for e.g. drinking water, cooling water, etc.	
	No industrial use of outer water	*Threats* = 0.0
	Some industrial use of outer water	*Threats* = 0.5
	Much industrial use of outer water	*Threats* = 1.0

A description of the water type codes that are referred to in this questionnaire can be found in Elbersen et al. (2003)

Table 3 Questionnaire for calculating E(Effects) of an exotic species

E total = $(H_{total} \text{ x } 9 \text{ x } S) + (H_{total} \text{ x } P_{total}/((9 \text{ x } S) + 1))$	
Habitat suitability = $H_{total} = (H_1 + H_2 + H_3) / 3$ Invasive Potential = $P_{total} = P_1 + P_2 + P_3 + P_4 + P_5 + P_6 + P_7 + P_8 + P_9 + P_{10}$	
H_1	Species is able to settle for at least some time $H_1 = 1$ Species is not able to settle for at least some time $H_1 = 0$
H_2	Species is able to settle and spread (by sexual or asexual reproduction) for at least a limited period of time $H_2 = 1$ Species is able to settle and spread (by sexual or asexual reproduction) for at least a limited period of time $H_2 = 0$
H_3	Species is able to settle and spread (by sexual or asexual reproduction) for years to come $H_3 = 1$ Species is able to settle and spread (by sexual or asexual reproduction) for years to come $H_3 = 0$
S	Species has been recorded in literature to have done substantial economical damage, i.e. of more than € 100.000, -, and/or has outcompeted a native species, at least locally $S = 1$ Species has not been recorded in literature to have done substantial economical damage $S = 0$
P_1–P_3: Potential to spread	
P_1	Is the species a r-strategist, i.e. it has relatively many offspring and becomes reproductive within a relatively short period of time? Yes: $P_1 = 1$ / No: $P_1 = 0$
P_2	Can the species survive in a relatively large range of environments? Yes: $P_2 = 1$ / No: $P_2 = 0$
P_3	Is the species present in the water column in at least one of its life-stages? Yes: $P_3 = 1$ / No: $P_3 = 0$
P_4–P_7: Potential to do ecological damage	
P_4	Can the species be such a strong food or space competitor that it can cause a significant decrease in the population size of a native species? Yes: $P_4 = 1$ / No: $P_4 = 0$
P_5	Is the species a predator or parasite that can cause a significant decrease in the population size of a native species? Yes: $P_5 = 1$ / No: $P_5 = 0$
P_6	Can the species contain/harbor a disease, parasite or toxin, which can cause a significant decrease in the population size of a native species? Yes: $P_6 = 1$ / No: $P_6 = 0$
P_7	Is the species an ecological engineer, aiding the settlement of other invasive exotic species? Yes: $P_7 = 1$ / No: $P_7 = 0$
P_8–P_{10}: Potential to do economical damage	
P_8	Can the species clog up pipelines or inlets? Yes: $P_8 = 1$ / No: $P_8 = 0$
P_9	Can the species cause physical damage to artificial structures like dikes, floating docks, sluices, etc. Yes: $P_9 = 1$ / No: $P_9 = 0$
P_{10}	Can the species cause economical damage by damaging fishing gear or by decreasing the population size of species with a commercial value? Yes: $P_{10} = 1$ / No: $P_{10} = 0$

towards exotic species are calculated. For compliance with the European Water Framework directive, EU countries have defined various water types varying in size, salinity, current strength and the substrate of the bottom. All water bodies in a country have been assigned to a water type with accompanying management goals.

The questionnaire for calculating *Threats* linked to a water body focuses on two main questions (Table 2): 1) *What threatens a water body?* A water body is given a high threat value when a large diversity of exotic species is present or when a high number of invasive species import vectors are present, like shipping or shellfish transport. This value is calculated by adding up the parameters T_1 through T_5 (Table 2). A total value of 0 indicates that virtually nothing threatens the water body, while a value of 5 indicates that there are several components/issues that seriously threaten the water body. 2) *What is threatened in a water body?* A water body is given a high threat value if it is used to extract water for industrial or drinking water purposes, or when it has a relatively high diversity of native, rare and/or endemic species. This value is calculated by adding up the parameters T_6 through T_{10} (Table 2). A total value of 0 indicates that the water body is not threatened, while a value of 5 indicates that the water body is highly threatened.

The questionnaire for calculating the *Effects* of an invasive species focuses on five aspects (Table 3):

1) *Habitat suitability.* Water bodies in which an exotic species can settle and expand its population are more vulnerable than water bodies in which exotic species can settle and survive, but cannot reproduce. The value is calculated using the formula $H_{total} = (H_1 + H_3 + H_3) / 3$, in which the parameters H_1, H_3, H_3 can each be given a value of 1 or 0, meaning H_{total} can have a value of 0, 1/3, 2/3, or 1 (indicating complete habitat suitability). When setting these parameters, one has to

decide whether the species is able (H_1) to survive (at least for a while), (H_2) to survive and reproduce, and/or (H_3) to survive, reproduce and settle in the water body in the long term.

2) *Damage done.* This value is based on the assumption that water bodies are more vulnerable to species that have already done a significant amount of economical and/or ecological damage, locally or elsewhere. The chance that a species that has never done recorded substantial damage in another area would do so in the selected water body is very small. This parameter gets a value of 1 when the species has already been recorded to have done more than € 100.000 (this amount was chosen subjectively, one can choose to use another amount) of damage, and/or when the species has been recorded to have outlasted a native species, i.e. a native species has at least locally gone extinct in an area because of this exotic species. If no such damage has been recorded, then damage done = "0".

3) *Potential to expand its population*. This value is based on the assumption that a water body is relatively more vulnerable to species that are able to expand their populations rapidly by means such as a relatively short life-cycle, the ability to spread through the water column, and/or the ability to settle in a wide variety of different habitats. This value is calculated by adding up P_1 to P_3 (Table 3). A species that is able to expand its population relatively quickly will get a value of "3" while those that cannot, get attributed a value of "0".

4) *Potential to cause mainly ecological damage*. This value is based on the assumption that a water body is relatively more vulnerable to species that cause ecological damage, which is not necessarily linked to any economical damage. The water body is more vulnerable to species that can compete strongly for space with native species and predatory species, species that can alter an environment in such a way that it promotes the settlement of consequential invading populations and those that bring non-native parasites and diseases. This value is calculated by adding up values P_4 to P_7 (Table 3). A species that can cause a lot of ecological damage is given a value of "4" and one that causes minimal ecological damage is given a value of "0".

5) *Potential to cause major economical* (*and ecological*) *damage*. This value is based on the assumption that a water body is vulnerable to exotic species that cause economical damage, which is not necessarily linked to any ecological damage. The water body is vulnerable to species that can cause physical damage to pilings or dikes for example, as well as species that have negative effects on populations of other economically important species (e.g. shellfish). This value is calculated by adding up values P_8 to P_{10} (Table 3). A species that can cause a lot of economical damage is given a value of "3" and one that causes minimal economic damage is given a value of "0".

The questionnaires calculating *Threats* and *Effects* can be used by any water manager, with the aid of a vast set of factsheets for each of the exotic species and water bodies concerned (Table 4, 5). The factsheets used in this paper were developed for the ministry (see Leewis and Gittenberger, 2007[4]) and can be applied for various

Table 4 The basis for the calculation of *Threats* is formed by fact sheets of water bodies, like the one below describing the water body "Waal", with an R16 WFD water type, i.e. fast flowing river/stream; bottom consisting of sand and/or gravel), in combination with the questions T_1 to T_{10} (Table 2)

FACT SHEET

Water body: Waal

WFD-type: R16 (fast flowing river/stream; bottom consisting of sand and/or gravel).

Industrial output into the water: Chemical waste disposal, Eutrophication (farm-land).

Invasive species import vectors / connectivity: Strong water currents: Import of exotic species upstream, Busy shipping route.

Biodiversity: Non-native species (~5, ~10, or >~20), ~20; Native species (~10, ~50, of >~100), ~50; Rare and endemic species (0, ~2, >~4), ~2.

Variety in habitats: Salinity,the salinity is constant, i.e. fresh water, throughout the water body; Currents, there is large variety in current velocity within habitats present in the water body, e.g. the shore and centre of the river vary strongly in current velocity; Substrate, both hard an soft bottom substrates are abundant in the Waal.

Recreational use: Minimal use by recreational fisheries.

Industrial extraction of water: Not present.

The WFD-type is coded according to Elbersen et al. (2003)

4 Leewis, RJ, Gittenberger A, 2007. Vulnerability of water types to exotics: Development of a methodology. TPS-report E001/07: 22 pp + annexes (in Dutch).

Table 5 The basis for calculating the *Effects* is constituted by the fact sheets of exotic species, like the one below describing the Red swamp crawfish *Procambarus clarkii*, in combination with the questionnaire in Table 4

Fact sheet: Red swamp crawfish *Procambarus clarckii*.

Habitat 1: The exotic species can in principal (at least temporarily) survive in: M1-M29; R1–R18.

Habitat 2: The exotic species can in principal survive and reproduce in: M1–M29; R2, R4–R18.

Habitat 3: The exotic species can in principal survive, reproduce and settle in the long term in: M1–M29; R2, R4–R12.

Damage done: The Red swamp crawfish has not been recorded to do substantial economical (> 100.000,- Euro) or ecological (causing a native species top go extinct) damage anywhere world-wide.

Potential to expand its population:

- De species is not a r-strategist.
- De species can live through in a wide variety habitats that have extreme abiotic differences, i.e. it can survive drought and freezing cold temperatures.
- De species is mainly present in the water column during the larval stage.

Potential to cause mainly ecological damage:

- The species is not a strong competitor for space.
- The species can be predator on small crustaceans, small fish, molluscs and the eggs/larvae of its relatives.
- The species can carry non-native diseases and parasites, that can infect the native crawfish.
- The species is not an "ecological engineer".

Potential to cause mainly economical (and ecological) damage:

- The species can not hamper the through flow of pipes and/or channels.
- The species is not know to do substantial damage to human artifacts like pilings or dikes.
- The species is not recorded to cause economical damage, because of its negative effect on the populations of economically important native species.

These questions lead to the appointment of values to the parameters "Habitat suitability" (H), in literature recorded economical and ecological damage done (D), and the hypothetical potential of becoming invasive based on the ecology, trades and characteristics of the species (P).

water body-exotic species combinations. The original fact sheets were written in Dutch by various experts; only the two examples in this paper were translated into English.

2.2 *Threats*, *Effects* and *Vulnerability* of the selected water bodies and species

The equation and the questionnaires described were applied to the above mentioned eight water bodies (Table 1) in combination with the selected thirteen exotic species in The Netherlands.

The *Threats* for the various water bodies are illustrated in Fig. 1. The *Effects* of the thirteen exotic species on these water bodies are illustrated in Fig. 2. The *Vulnerability* of the water bodies towards the exotic species is illustrated in Fig. 3. The resulting vulnerability values for an exotic species on various water bodies can also be presented on a geographical map using colour codes. The map in Fig. 4 illustrates an example, using the vulnerability of water bodies to the invasive species, the mystery didemnid *Didemnum vexillum*.

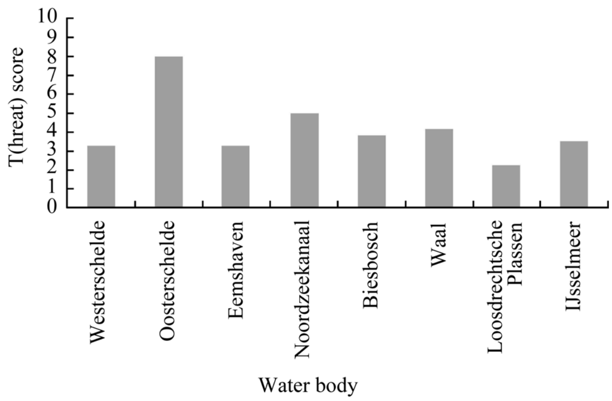

Fig. 1 Threat scores of the eight water bodies

3 Discussion

Approaches to this issue that were developed elsewhere are virtually all based on the influence that a certain specific exotic species has on the system (terrestrial or aquatic) concerned (Olenin et al., 2007). No other method takes the search for the vulnerability of the system as a focus, considering that the vulnerability is

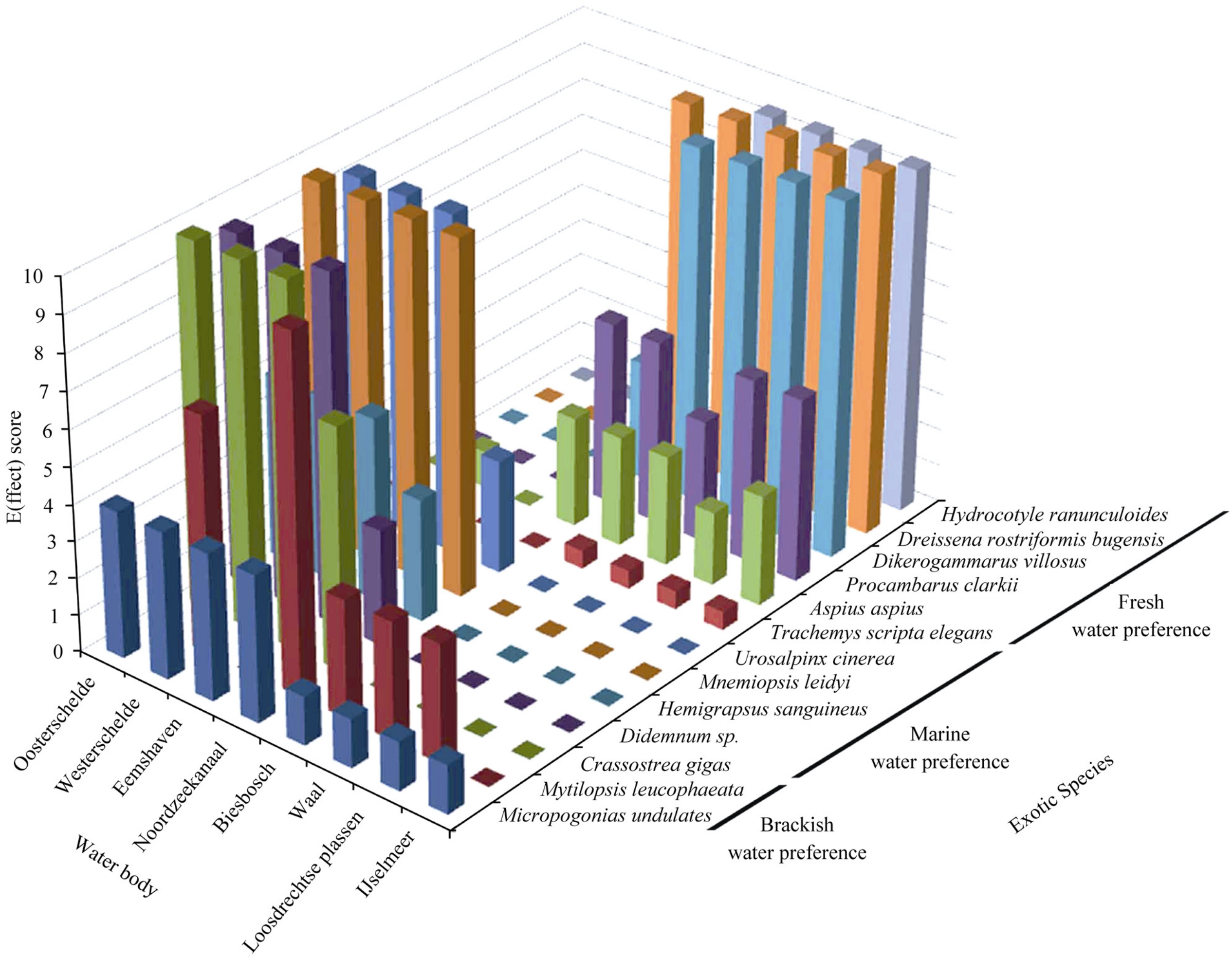

Fig. 2 Effect scores of the thirteen species

dependent on the effect(s) of alien species along with aspects that threaten a water body and aspects that are threatened in a water body. The methodology described here aims at providing a tool that can be used to comply with the European Water Framework Directive and taking exotic species into account. The methodology provides the possibility to calculate the vulnerability of Dutch water bodies to invasive species. As the presence of invasive species in a system will in most cases heighten its vulnerability to even more invasive species, this aspect has been specifically included in the questionnaires. The method is relatively easy to use by water managers and gives solid, consistent results. Water managers will generally have the required knowledge about the water bodies to use this methodology. In most cases they do not possess the required knowledge about the exotic species. A vast set of fact sheets of these exotic species, still to be drawn up, could be used to solve this problem. The new method combines features from several methods developed in other countries (Arbačiauskas et al., 2008; Cardoso and Free, 2008; Olenin et al. 2007), resulting in a more extended and complex but therefore also more compatible method. An important test would be an intercalibration of the various approaches that are known. We believe this is could be the subject for another paper. If the Vulnerability value resulting from the presented method here is not comparable with the resulting values for methods used outside of The Netherlands, the formula V = (T + E) / 2 can be changed into parameters that are more compatible and therefore comparable. The *relative* values were chosen aiming at giving a *relative* value of vulnerability. One can choose to treat certain aspects such as parameters as more important by attributing a different weight to them or by giving them a higher maximum value than is proposed. Optimizing these values can be done over time based on the best available data. It is better to use the same weights and maximum values in any application of this methodology however, in order to be able to compare the results in the easiest way.

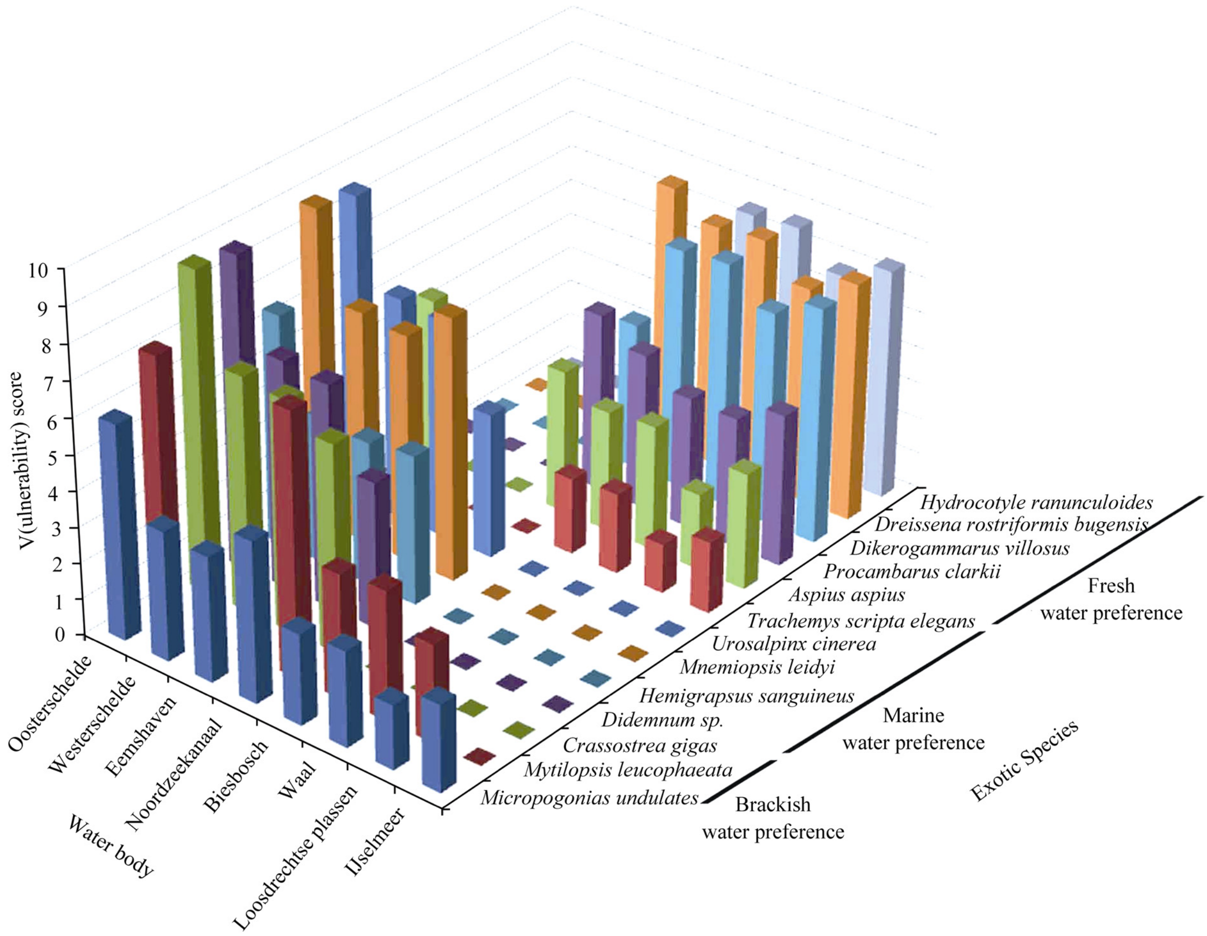

Fig. 3 Vulnerability scores of the eight water bodies (Table 1) for the thirteen species (Table 2)

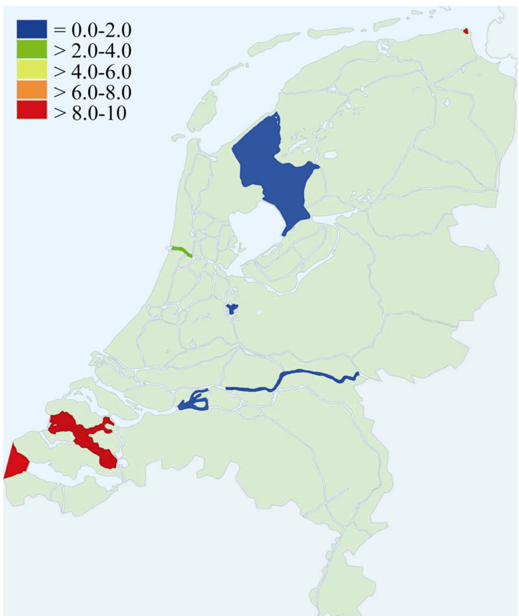

Fig. 4 The Vulnerability scores of water bodies can be illustrated with color codes on a map as is shown here for vulnerabilities of water bodies for the exotic species *Didemnum vexillum*

The colours blue and green indicate that the water body is not or virtually not at risk, while orange and red indicate that the water body is vulnerable to extremely vulnerable

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