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CONSTRUCTED WETLANDS: TOOLS FOR ADAPTATION UNDER CLIMATE CHANGE

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Abstract

Where climate change mitigation often focuses on energy, water safety and reliability has become a symbol of adaptation. Around the world, water, or its absence, has become one of the greatest risks of changing climate.

Wetlands are uniquely placed at the interface between land and water, to act as natural buffers and protect our freshwater and estuarine environments. This paper looks at the results of a PhD study that was triggered by an emerging realisation, internationally, that constructed wetlands can provide the variety of functions which natural wetlands perform, without causing harm to natural wetlands. It looks at the success of natural wetlands in carrying out a variety of functions, and how a constructed wetland could be designed to optimise one or several of these functions. The specific focus is balancing water quality and treatment requirements with other priorities. Many of wetlands' potential functions can help in sustainable water management or climate change adaptation.

With more prolonged droughts and intense seasonal rains, wetlands can buffer against floods, and be a reserve and habitat during drought. In our quest for efficient water use, wetlands play a key part in water recycling at all levels. From simple vertical systems, to large scale mine water treatment, the ability of wetlands to filter water will enable us to face water security issues that may arise from future climate change, and adapt to our new, water scarce, environment. When our waterways are more stressed than ever, wetlands can be used to filter runoff and reduce water pollution, relieving aquatic ecosystems of additional concentrations during low flows. Most importantly, wetlands promote landscape scale management by being integrally linked with surrounding parts of the landscape. This means that for their effective management, the whole of the landscape must be considered. Such integration of management at the landscape scale makes the management of all issues in that landscape more effective, as each individual issue is treated as part of a whole.

The PhD designed and constructed a prototype tool which can be used to design wetlands according to their multiple functions. A decision support system and lookup tables facilitate the selection of various wetland cells, and the nutrient removal capacity of the cell combination is then assessed. The prototype design model and decision support system incorporate environmental, social and economic characteristics as well as nutrient removal, going beyond simple engineering to a holistic integration of factors. This tool will enable constructed wetlands to themselves be tools in sustainable water management and climate change adaptation.

Introduction

Where climate change mitigation often focuses on energy and transport, water safety and reliability has become a symbol of adaptation. All around the world, water, or its absence, has become one of the greatest risks of a changing climate. Whether through flood, salt water intrusion, drought, sea level rise, or glacier melt, the availability of freshwater is of concern for both people and the environment. In parallel, water quality is at the centre of health issues both for people and ecosystems; key to maintaining a healthy, complete, hydrological cycle, essential for survival.

Wetlands are uniquely placed, at the interface between land and water, to act as natural buffers and protection to our freshwater and estuarine water environments. This study looks at the natural versatility and variety of wetlands and how these assets may be harnessed, in constructed wetlands, to make tools for efficient water management; they can then promote healthy waters, facilitate adaptation to climate change, or provide buffers to floods among many others.

Our waterways are more stressed than ever due to climate change and pressures on water demand and quality. Wetlands can be used to add resilience to many parts of the hydrological cycle, both in the built environment by promoting reuse, and to waterways by filtering runoff and relieving aquatic ecosystems of additional pollutant concentrations during low flows.

Wetlands' natural ability to filter water can be a large asset in encouraging public acceptance to the inevitable increase in recycled water use by acting as an extra, natural, treatment barrier. With highly variable inflows into storages, cycling dam water through a constructed wetland can help combat eutrophication and suspended solids when water in the storages is expected to remain there for as long as possible.

Wetlands can play a key part in our quest for efficient water use as an aide to water recycling at all levels. From simple vertical greywater systems, to large scale tailings treatment at a mine or power station, the ability of wetlands to filter water will enable us to face water security issues that may arise from future climate change, and adapt to our new, water scarce, environment.

Wetlands, if well placed and well managed, could help the migration of coastal species, struggling to keep pace with sea level rise. As a brackish interface, adaptation of plant and animal species from a dry to a saline environment may be facilitated by providing a brackish 'intermediate' step.

Wetlands can also be used as buffers against increasing variability in rainfall. With more prolonged droughts, and intense seasonal rains, wetlands can buffer against floods, and be a reserve and habitat haven in times of drought. Special design characteristics can reduce evaporation during hot dry weather, while providing thick vegetation stands to slow and disperse flood waters, reducing damage to fences, homes and danger to cattle and crops.

This paper is taken from a PhD study which looks at the design of wetlands. During the literature review and early stages of the research, a clear gap was identified. Although many wetland treatment systems are implemented and researched worldwide, there were few tools which could be used in order to identify design criteria for wetlands based on the possible multi-functions other than wastewater and stormwater treatment requirements. This meant there was no tool where prioritisation of many functions was linked with wetland design. It was decided that a tool could be generated that would link design and function in a constructed treatment wetland so that a wetland could be designed according to its functional requirements, and subsequently a set of design parameters might be assessed in terms of treatment capacity. Important challenges were encountered and lessons were learnt from this study which will hopefully contribute to constructed wetland design in the future.

The concept of constructed wetlands harnessing the variety of functions which natural wetlands perform, without causing harm to natural wetlands, triggered this study. The study aimed at duplicating the success of natural wetlands in carrying out a variety of functions, going further to investigate how a constructed wetland could be designed to optimise one or several of these functions; balancing water quality and treatment requirements with other priorities.

The initial question that presented itself, was whether a model could be built that could design a wetland based on an existing input water quality and the required output water quality; and whether such a model could be reversible, allowing the assessment of a design based on input parameters and projecting a potential output. Additionally, the reversible model, which would be focussed on the water quality element, was to be linked with other wetland functions, or externalities such as food and fibre products, landscape connectivity, flood buffering or education services to mention but a few.

The following questions were therefore addressed by the PhD:

1. Can a model be created that facilitates holistic wetland design based on waste water requirements and other functions
2. To what degree can the model anticipate the nutrient removal capacity of this wetland?
3. Can the model integrate biophysical variables, wetland design rules and externalities of society in order to simulate and assess a wetland system, generating decision alternatives?
4. Can the model be generated in such a way as to accept input in a broad range of data types but still present useful results with accuracy and precision?
5. To what degree can an interactive DSS be used in facilitating decision making for water management?
6. Can this entire model be structured in such a way as to progress with future research and development?

In developing the model, the study demonstrated the inefficacy of a reversible model design, and investigation began on a modified design which could achieve a similar objective albeit with a modified emphasis. The objective had been refined through better understanding of the literature, moving towards an optimal tool that would facilitate holistic wetland design in the context of sustainable water management. The ‘external’ elements took on greater importance, whereas the nutrient removal ability of the wetland, while still important, was not deemed in need of an accurate predictive tool. This was on the basis that precise nutrient removal is addressed by many other technologies, and while wetlands filter nutrients, their optimal design is one that capitalises on wetlands’ many functions and values thereby making nutrient removal one of many elements. A more approximate nutrient removal capacity would then be an adequate output for the assessment part of the model.

The Process of Designing the Model

The process of designing a model took the study through many challenges to finally lead to a final prototype model in Microsoft Excel.

There are many interlinking relationships one can observe in nature. A wetland system, natural or constructed, has an incomputable number of inter-relations between its constituents with an inexplicable and incomprehensible variety of relationships. The dependencies and inter-dependencies form patterns which we then study, and from these patterns attempt to model future scenarios. This model, like all models, simplifies a system to a core of parameters and relationships, however attempts to include relationships that still exhibit the chaotic elements observed in nature. It does this by including speculative non-numerical relationships in a form which may allow the information and knowledge to contribute to decision making despite possible lack of mathematical clarity or transferability. In this way, the potential multi-functions of a wetland and their resulting ripples in the wetland design and processes, can be better understood and then assessed and prioritised.

This immediately directs the building of a tool toward a holistic model, in spite of the multitude of links that can never be fully nor accurately described. Instead a more generic association between desired function and design is made, resulting in more variable level of detail in results, particularly with regard to nutrient removal projections.

Variables were categorised into four compartments: geometric, nutrient, landscape and community. The links between design compartments (geometrics) and each of the other compartments were complemented with links *within* various compartments. A decision support system (DSS) was established that helped the user identify their priority functions for the wetland and which highlights the associated links of relevance.

To simplify the process of wetland design, wetland cells were characterised. These pre-drawn cells have certain fixed characteristics (eg. depth) and associated vegetation types as well as dimensions which can be expanded or shrunk but retain their relative proportions. With the help of the DSS, the user can then put the wetland cells in various orders to optimise the efficacy of the wetland in performing the desired functions. The ordering of the wetland cells significantly reflects the nutrient removal requirements of the wetland, and a simple macro in Microsoft Excel identifies the nutrient priorities. These priorities, along with a set of rules, allow the user to consider nutrient removal requirements when designing the wetland. The purpose of the rules are to make the user aware of reverse processes, or inhibiting processes which would reduce the efficacy of their chosen wetland 'train'.

A prototype assessment model was then built, using the work of Kadlec & Knight (1996) and Reed (1995) as a foundation, in an attempt to anticipate the nutrient removal capacity of certain designs. Several important obstacles were discovered, which made this part of the model unsuccessful. Some of these challenges have since been mentioned in the second edition of Kadlec & Knight (1996) and Kadlec & Wallace (2009) confirming the challenges encountered are not surmountable without considerable further research on wetland systems. Some of the challenges encountered were:

1. Wetland design parameters not adequately represented mathematically

The initial model attempted to model the nutrient removal capacity of a wetland design based on existing (adapted) equations (K&K). It was found that some significant elements of wetland design were not represented by the equations, the most important of which was vegetation.

2. Site specific constants, coefficients and dummy variables

Constants used in descriptive modelling are not always true constants, but rather coefficients or dummy variables. These makes them non-transferable outside their specific wetland context. Additionally, evolution of these parameters is expected and this could not be modelled. This problem is essentially the one of using descriptive modelling for predictive purposes.

3. Using descriptive modelling for predictive modelling

Some relationships were much easier to derive in one direction, but not in another. A typical example is the use of differential equations to describe nutrient flow in a wetland. These equations cannot be reversed to estimate the spatial distribution of nutrients in a hypothetical wetland.

4. **Circular references in Microsoft Excel**
The 'reversible model' created circular references in Microsoft Excel, where the model would search for answers within its own database, but then attempt to solve an equation with an unsolved equation. The linear end to end design of the modified model removed this issue.

The first point in particular led to the slight change in emphasis in the purpose of the model, acknowledging that parameterising and simplifying the inter-relationships between design and function into mathematical equations left a significant amount of information out. As a result of the model design process, this study suggests that for a tool to be useful, the model needs the capacity to include non-mathematical links. The DSS was designed with this in mind and is now the core of the model. It highlights the requirement for the user to consider 'externalities' in order to best capture the many complexities of wetland interactions.

The Final Model Design

The Design-A-Wetland model has a decision support system at its core, with which a user can design several wetland combinations according to the priorities and end purpose for the wetland. The designing of the wetland is based on the linking together of various wetland cells with predefined parameters (some of which can be altered by the user) into different combinations. A decision support system and lookup tables facilitate the selection of various cells. A basic assessment model was also designed to assess, on a nominal level the nutrient removal capacity of the cell 'train'. Significant challenges were encountered adapting descriptive modelling to predictive modelling due to transferability issues. The purpose of the model was revised, and a balance between nutrient removal capacity and other benefits of wetlands was reached. This included design extras and management options to complement the wetland cell design that would be assessed by the assessment model.

Although only a prototype model has been created (with only 5 wetland cells and 5 nutrients), the decision support system central to the design incorporates 5 more wetland cells as well as environmental, social and economic characteristics beyond the nutrient removal capacity of the system. This is done by linking design elements with various wetland functions.

Following the failure of a reversible design, a new Design-A-Wetland model framework was designed to include:

- A decision support system linking functions with design parameters;
- A set of wetland cells (combinations of design elements), that can themselves be used in many combinations according to various priorities;
- A wetland assessment prototype model to test the nutrient removal capacities of the nominal wetland designed based on the wetland cells;
- Additional design elements that can be added the baseline wetland cell to add functionality to the wetland, but which are not tested in the assessment model;
- Management options which enhance several of the potential wetland functionalities.

As part of the wetland design process, the user follows the following steps:

1. Prioritise the functions of the model
2. Prioritise the nutrient removal processes
3. Insert input into the DSS
4. Sort wetland cells according to the priority of nutrient removal and other functions
5. Assess the wetland cells for their nutrient removal capacity
6. Add design extras and management options judiciously to optimise chosen functions

The DSS has two purposes: identifying a suitable set of wetland cells, and their order, using the nutrient removal priorities of the user; and, using the functional priorities of the user, identify which wetland cells cater to these, plus any additional design extras or management requirements which are suitable.

The possible wetland functionalities that can be selected, and prioritised, by the user, to aid in wetland cell choice include:

- Nutrient removal – N, P, BOD, FCU, Metals etc.
- Habitat – fish, fowl, reptiles and amphibians, migratory, other
- Safety
- Aesthetic
- Pest control – vegetation, animal
- Erosion control
- Acidity – reduce, increase, cope
- Salinity – reduce, cope
- Flood buffer
- Product – animal, food (eg rice), fibre
- Education – general, involved
- Sequestration – carbon, methane

And some of the associated design alternatives, whose full impacts on nutrient removal are not included in the assessment model are:

- Edges
- Riffles
- Pre-treatment
- Boardwalks and information boards
- Vegetation species
- Islands
- Flood bypasses
- Impermeable lining
- Fences

And linked with those, some management requirements:

- Harvesting
- Chemical addition
- Monitoring
- Dilution
- Changing water levels
- Pest control
- Desilting
- Periodic drying/flushing

Figure 1 shows a screen shot of the DSS with the questions asked of the user in order to prioritise the inclusion of the above elements. Figure 2 shows the colour coded system which links the answers provided by the user to the wetland cells, management requirements and design extras.

Wetland Cells are combinations of designs associated principally with nutrient removal. Wetland cells are key wetland characteristic-combinations with associated functions which are used in this Design-A-Wetland model. These wetland cells are then inputted into the prototype part of this model which assesses the wetland design.

The five wetland cells included in the prototype model are:

- Sediment basin
- Open water
- Deep marsh
- Marsh
- Shallow Marsh

The Other Cells include:

- Grassy bank
- Detention pond
- Striated/Banded
- Subsurface vertical flow
- Subsurface horizontal flow

The prioritisation of these wetland cells is done using the DSS, however the ordering of these occurs in the model and is based on a set of rules, and on the nutrient removal requirements identified by the user. Figure 3 shows a screen shot of part of the cell prioritisation which ranks the nutrient removal requirements.

The assessment model prototype consists of:

- An entry form where the user can enter input concentrations, the order of wetland cells, and some other required information such as the total average flow through the wetland. The user can also enter the desired output concentrations onto this form to assess the actual success against required concentration reductions.
- A set of spreadsheets with: wetland cell information that gets called upon depending on the user's selection in the entry form; constants and coefficients; and geometric elements, including a calculation for each wetland cell size.
- A process model generating an output for each cell, and using it as the input for the next cell and a final display showing key results.

The prototype includes a number of non-functional parameters as an indication of what the full model might include. Figure 4 shows an example screen shot of the entry form for the wetland cell order.

Conclusions:

In developing the model, the study demonstrated the inefficacy of several of its initial model designs and the emphasis of the model's function shifted. Finding ways to link function and design led to a shift in priorities for the purpose of the model. This emphasised that nutrient removal alone as a function did not represent the full capacity of wetland, or capitalise on the opportunities which wetland systems offered. It was clear that an useful wetland design tool could not ignore the multiple wetland functions.

This study encountered many challenges attempting to create a tool that would design a wetland whilst also incorporating relevant design characteristics that would allow the inclusion of many functions beyond nutrient removal. The process of overcoming these issues led to the conclusion that precise and accurate anticipation of the nutrient removal efficiencies of a wetland would be compromised when incorporating other design parameters which cater to other functions. This study also justifies why the ability to accurately predict nutrient removal should be secondary compared to incorporating other functions. It also suggests that combining such a model with existing wetland models such as MUSIC would be beneficial to users designing wetlands. The benefits include raising awareness of the other functions and design elements which can be included into wetland design, as well as their impact on nutrient removal. Due to the compatibility of this model design with existing nutrient removal prediction tools, it was deemed that the need for accurate and precise nutrient removal assessment was not commensurate to the effort required to develop this function. As only one of several goals of this model, the emphasis was slightly rearranged and modified questions were generated. This does not eliminate the requirement, post construction, to monitor what goes in and out of the water column, a process which is common and supported by high level descriptive modelling.

In attempting to develop a predictive model for the evolution of a wetland, it was concluded that a constructed system evolves, becoming a living ecosystem and inevitably acquires chaotic characteristics. It was also concluded that it is these chaotic characteristics which are required for optimal function of the wetland, and yet their very chaotic nature complicates our interaction and control over the ecosystem.
One of the key recognitions of this project is that a natural living system such as a wetland ecosystem cannot be fully and holistically described or even understood, let alone modelled. This is because, as with all models for ecological systems, the wetland model is a multi-dimensional system (Howell et. al. 2005).

Exploring the literature on existing modelling is what enabled the creation and identification of links, simple and complex, between function and design, which this model uses as its foundation. It was concluded that each wetland will inevitably have a set of primary, secondary and incidental functions. Constructed wetlands, once built, evolve into natural systems with chaotic characteristics (required for them to be effective), making nutrient removal inherently hard to predict, and as this study concludes, rarely required for decision making. This is not as detrimental to the wetland design process as would be expected. From the water treatment perspective, wetlands are not the optimal technology for precise and high level nutrient removal, due to the plethora of other treatment technologies available for high level water treatment. Wetlands are flexible, resilient and adaptive, and it follows that their optimal use is one that takes advantage of these strengths. This study suggests that being able to design a tool that emphasises flexible and multiple outcomes serves a greater purpose than simple water treatment, and it is with this in mind that the model was created.

This study suggests that, although we work hard to acquire the knowledge to control a system, this control must be relinquished, willingly and actively to reach the optimised functioning that the chaotic nature of an ecosystem offers, and a fully controlled system doesn't.

This study concludes that wetland design must go beyond the simple engineering and nutrient removal and become holistic, integrated systems which capitalise on the natural versatility which wetlands acquire as they evolve. This will enable constructed wetlands to be useful in many contexts. For example in combating water quality and management issues, particularly with relation to climate change. Such a design would be flexible and adaptive and applicable in many contexts.

References

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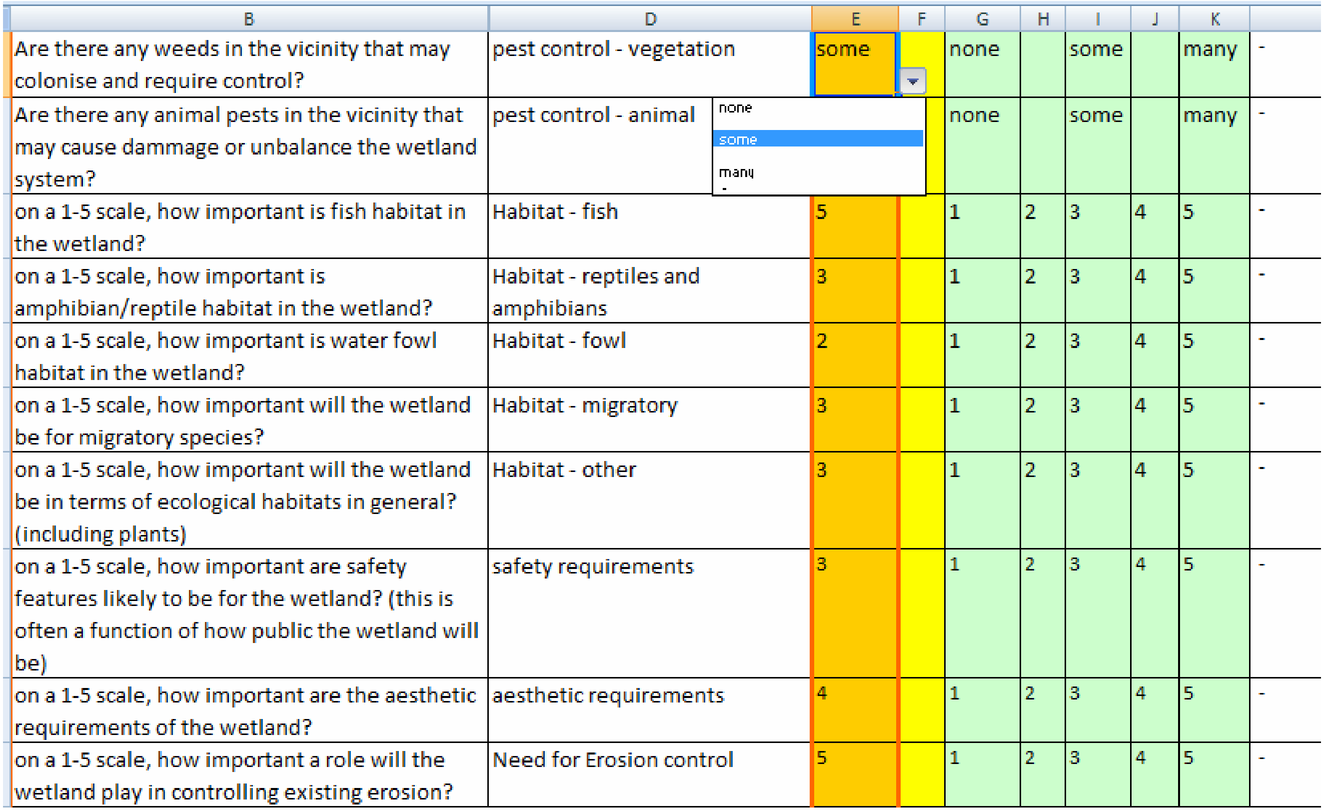
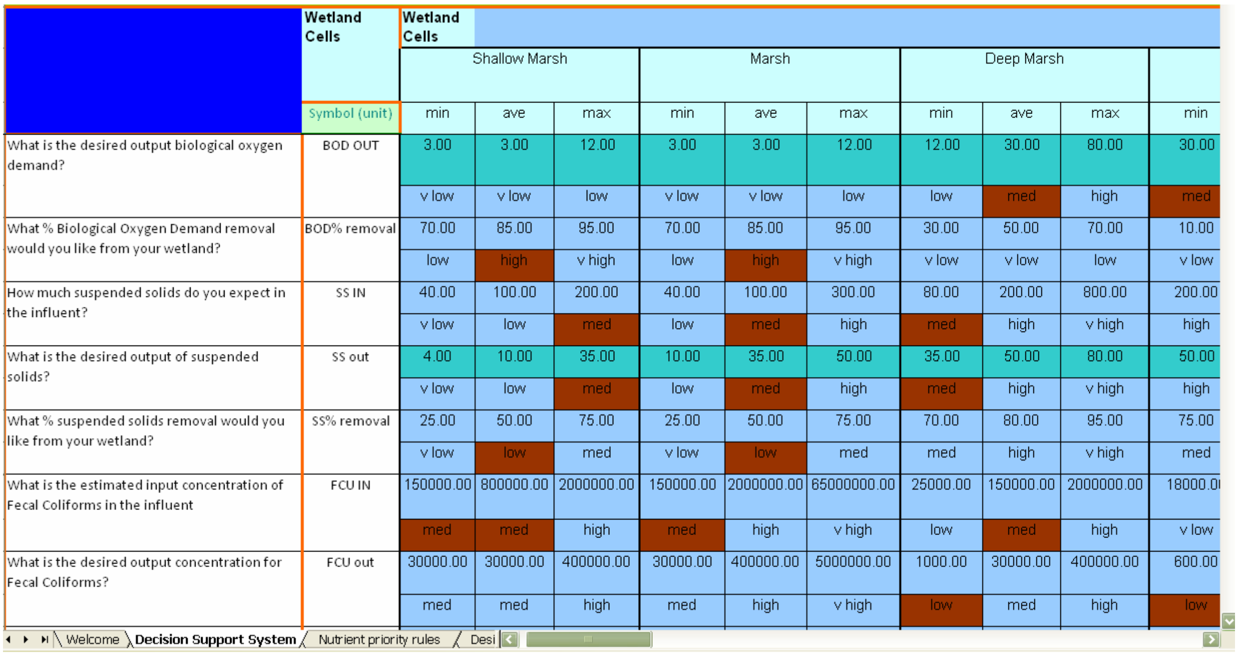


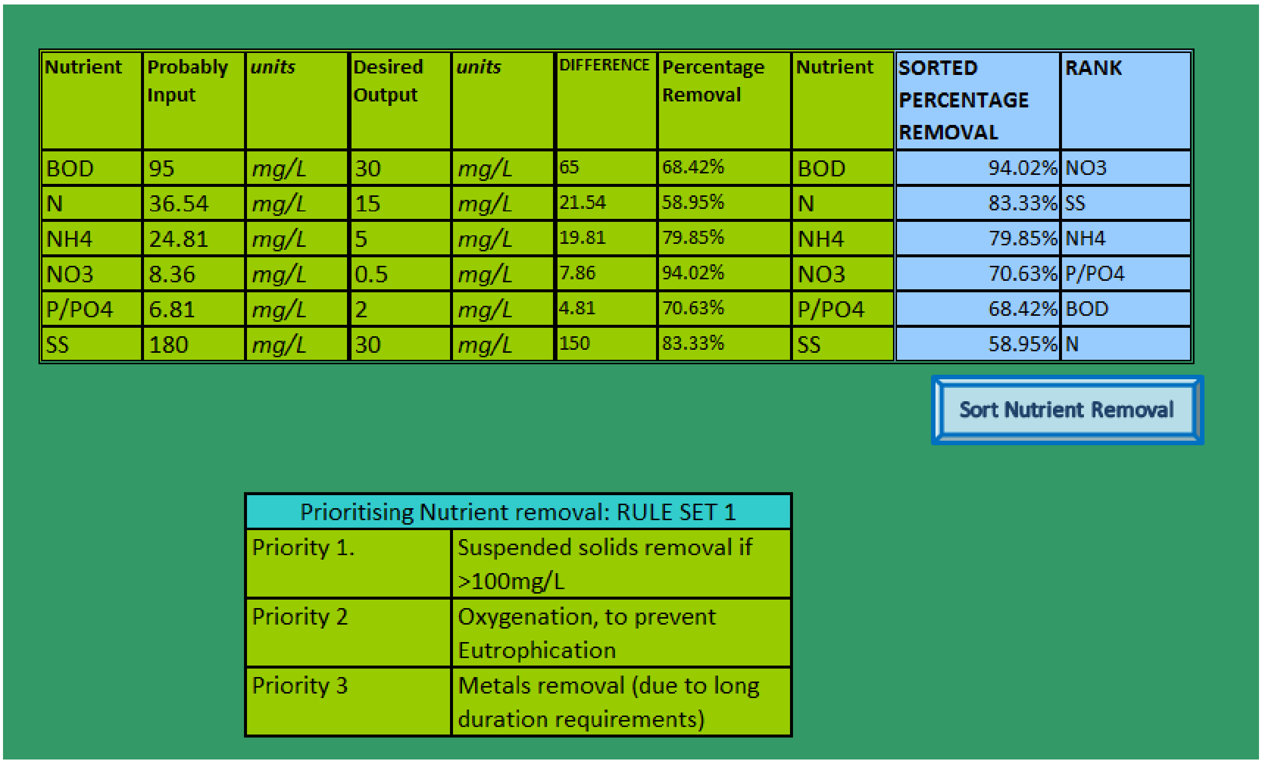
B	D	E	F	G	H	I	J	K	
Are there any weeds in the vicinity that may colonise and require control?	pest control - vegetation	some		none		some		many	-
Are there any animal pests in the vicinity that may cause dammage or unbalance the wetland system?	pest control - animal			none		some		many	-
on a 1-5 scale, how important is fish habitat in the wetland?	Habitat - fish	5		1	2	3	4	5	-
on a 1-5 scale, how important is amphibian/reptile habitat in the wetland?	Habitat - reptiles and amphibians	3		1	2	3	4	5	-
on a 1-5 scale, how important is water fowl habitat in the wetland?	Habitat - fowl	2		1	2	3	4	5	-
on a 1-5 scale, how important will the wetland be for migratory species?	Habitat - migratory	3		1	2	3	4	5	-
on a 1-5 scale, how important will the wetland be in terms of ecological habitats in general? (including plants)	Habitat - other	3		1	2	3	4	5	-
on a 1-5 scale, how important are safety features likely to be for the wetland? (this is often a function of how public the wetland will be)	safety requirements	3		1	2	3	4	5	-
on a 1-5 scale, how important are the aesthetic requirements of the wetland?	aesthetic requirements	4		1	2	3	4	5	-
on a 1-5 scale, how important a role will the wetland play in controlling existing erosion?	Need for Erosion control	5		1	2	3	4	5	-

Figure 1: A screen shot from the DSS showing a question, the related function, the drop down menu and the guideline values to help the user select from the drop down menu.



	Wetland Cells	Wetland Cells									
		Shallow Marsh			Marsh			Deep Marsh			
	Symbol (unit)	min	ave	max	min	ave	max	min	ave	max	min
What is the desired output biological oxygen demand?	BOD OUT	3.00	3.00	12.00	3.00	3.00	12.00	12.00	30.00	80.00	30.00
		v low	v low	low	v low	v low	low	low	med	high	med
What % Biological Oxygen Demand removal would you like from your wetland?	BOD% removal	70.00	85.00	95.00	70.00	85.00	95.00	30.00	50.00	70.00	10.00
		low	high	v high	low	high	v high	v low	v low	low	v low
How much suspended solids do you expect in the influent?	SS IN	40.00	100.00	200.00	40.00	100.00	300.00	80.00	200.00	800.00	200.00
		v low	low	med	low	med	high	med	high	v high	high
What is the desired output of suspended solids?	SS out	4.00	10.00	35.00	10.00	35.00	50.00	35.00	50.00	80.00	50.00
		v low	low	med	low	med	high	med	high	v high	high
What % suspended solids removal would you like from your wetland?	SS% removal	25.00	50.00	75.00	25.00	50.00	75.00	70.00	80.00	95.00	75.00
		v low	low	med	v low	low	med	med	high	v high	med
What is the estimated input concentration of Fecal Coliforms in the influent	FCU IN	150000.00	800000.00	2000000.00	150000.00	2000000.00	65000000.00	25000.00	150000.00	2000000.00	18000.0
		med	med	high	med	high	v high	low	med	high	v low
What is the desired output concentration for Fecal Coliforms?	FCU out	30000.00	30000.00	400000.00	30000.00	400000.00	5000000.00	1000.00	30000.00	400000.00	600.00
		med	med	high	med	high	v high	low	med	high	low

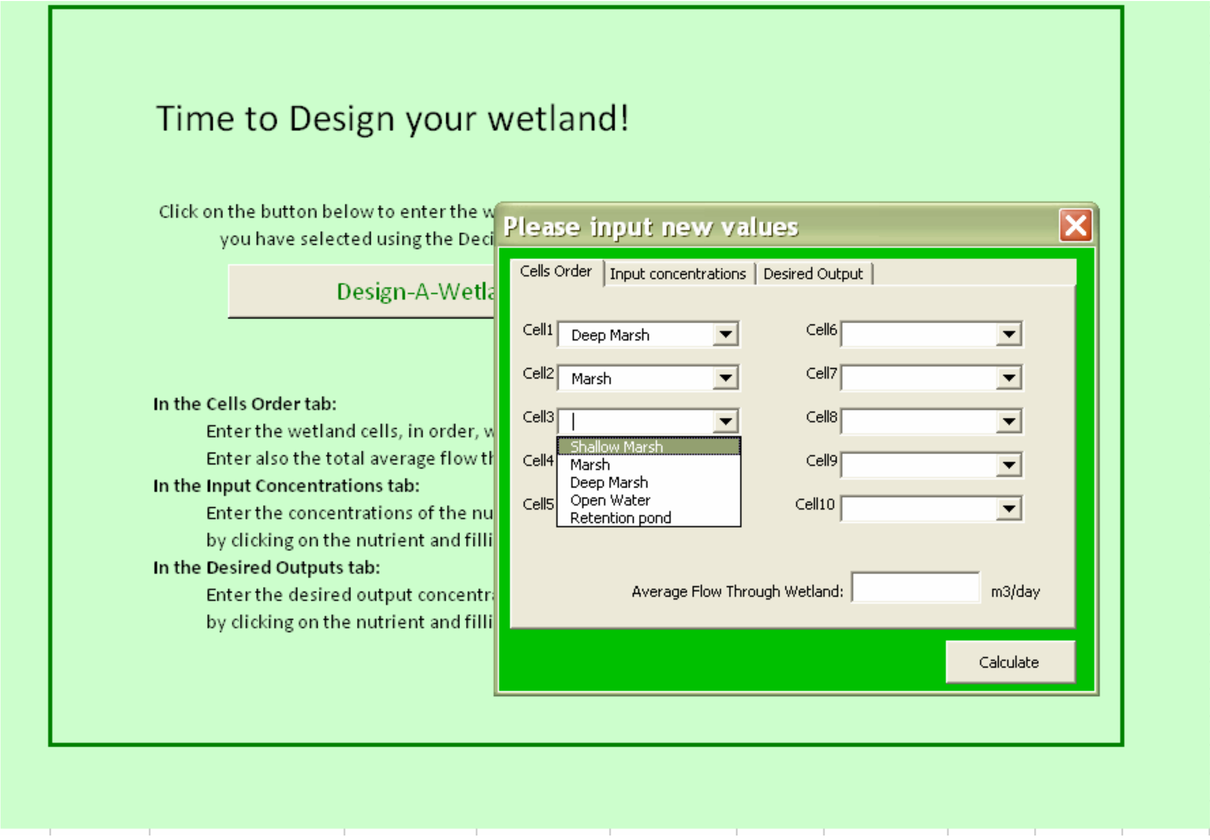
Figure 2: A screen shot of colour coding which associates the user's answers to the questions with various wetland cells. In this example, Shallow Marsh, Marsh and Deep Marsh.



Nutrient	Probably Input	*units*	Desired Output	*units*	DIFFERENCE	Percentage Removal	Nutrient	SORTED PERCENTAGE REMOVAL	RANK
BOD	95	*mg/L*	30	*mg/L*	65	68.42%	BOD	94.02%	NO3
N	36.54	*mg/L*	15	*mg/L*	21.54	58.95%	N	83.33%	SS
NH4	24.81	*mg/L*	5	*mg/L*	19.81	79.85%	NH4	79.85%	NH4
NO3	8.36	*mg/L*	0.5	*mg/L*	7.86	94.02%	NO3	70.63%	P/PO4
P/PO4	6.81	*mg/L*	2	*mg/L*	4.81	70.63%	P/PO4	68.42%	BOD
SS	180	*mg/L*	30	*mg/L*	150	83.33%	SS	58.95%	N

Prioritising Nutrient removal: RULE SET 1	
Priority 1.	Suspended solids removal if >100mg/L
Priority 2	Oxygenation, to prevent Eutrophication
Priority 3	Metals removal (due to long duration requirements)

Figure 3: A screen shot of the prioritising screen based on nutrient removal and the rule set 1.



Time to Design your wetland!

Click on the button below to enter the w
you have selected using the Deci

In the Cells Order tab:
Enter the wetland cells, in order, w
Enter also the total average flow th

In the Input Concentrations tab:
Enter the concentrations of the nu
by clicking on the nutrient and filli

In the Desired Outputs tab:
Enter the desired output concentr
by clicking on the nutrient and filli

Please input new values

Cell1: Deep Marsh
Cell2: Marsh
Cell3:
Cell4:
Cell5:
Cell6:
Cell7:
Cell8:
Cell9:
Cell10:

Average Flow Through Wetland: m3/day

Figure 4: A screen shot of a user filling in the three tabs, in this instance the wetland cell order