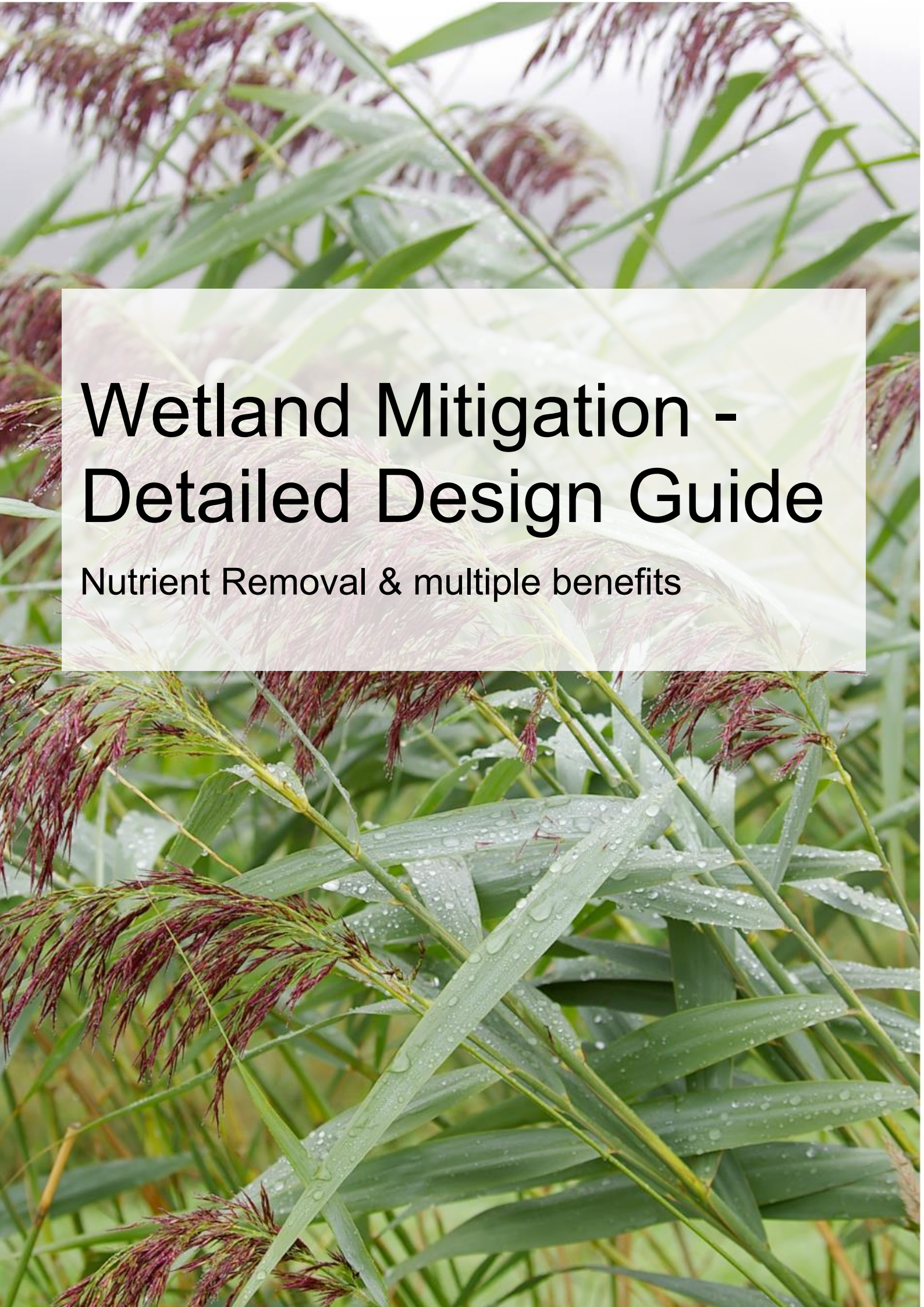

Wetland Mitigation - Detailed Design Guide

Nutrient Removal & multiple benefits

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Prepared by:

Robert McInnes (RM Wetlands & Environment Ltd)
Dr Matthew Simpson (35percent)
George Rose (GR Water Engineering)
Dr Geoff Sweaney (Wetland Engineering)
Catherine McIlwraith (The Rivers Trust)
David Johnson (The Rivers Trust)

Reviewed by:
Dr Gabriela Dotro (Constructed Wetland Association & NbS Future)
Dr Andrew Freeman (Constructed Wetland Association & ARM Group)

Contents

Foreword

This detailed design guide is intended to be used by experienced designers and delivery organisations who have limited experience of wetland design for nutrient removal but significant experience of designing other types of green engineering. It has been prepared by wetland designers with over a combined 100 years of design experience and reviewed by experts from the Constructed Wetland Association (CWA). The guide has been partly funded by Natural England.

Executive summary

This guide leads the reader through the design process required for a nutrient removal wetland. If the information available is sufficiently accurate, the average annual nutrient load removal of the wetland can be predicted with confidence at the design stage – **quantified nutrient removal wetlands**. However, if the information available is less certain, the guide can still be used to design an effective nutrient removal wetland, but the removal efficiency cannot be predicted in terms of the final concentration or total load removed – **unquantified nutrient removal wetlands**. Monitoring will be required to give the required level of confidence of the wetlands' nutrient removal efficiency. The seven design stages are identified below.

Design objectives require the characterisation of both the quality of the influent and the required water quality leaving the wetland. This characterisation defines the key parameters required for the design and the level of confidence that can be achieved from the design calculations. Multiple benefits and sustainability are also key objectives that are considered at each stage of the design process.

The **feasibility and outline design** starts by estimating the wetland area which allows a meaningful feasibility assessment to be conducted. The constructed wetland hub has been developed to support the feasibility and outline design stage of the work.

Planning and permitting guidance are summarised in a flow diagram with supporting narrative and advice notes based on experience of delivering wetlands in England. A list of consultees and key considerations are also provided.

The **detailed design** stage goes into more detail about the constraints (usually site specific levels, ground conditions and groundwater depth); hydraulic performance; water depth and management; vegetation communities and soils required for the design of an effective nutrient removal wetland.

The **construction and commissioning** stage includes site clearance; hydrological commissioning; vegetation establishment and example management plans.

Monitoring, operation and maintenance of wetlands is required throughout the design stages. Baseline monitoring is required to inform the outline and detailed design while monitoring at equilibrium is required during commissioning. Once the wetland is fully operational monitoring is required to support maintenance and adaptation and to identify if the quality or quantity of water entering the wetland changes.

Finaly the **costings** stage of the report provides guidance on the relative costs for each stage of the process along with an identification of the key uncertainties and example costings from recent project.

The design process described above is supported the Constructed Wetland Hub. The information in the Hub should be used with this guidance to ensure that the wetland design is effective for nutrient removal and delivers multiple benefits, maximising the wetlands contribution to catchment restoration.

Introduction

Background

Across England, nutrient pollution is an urgent problem for freshwater and estuarine ecosystems which provide a home to a multitude of important plant, bird, fish and insect species. Increased levels of nutrients, primarily nitrogen and phosphorus, can alter and accelerate the growth of certain plants, disrupting natural processes and devastating wildlife. Increasing levels of nutrients in the aquatic environment can also impact on human society through changes in fisheries, degraded aesthetics, loss of recreational opportunities, increased health risks and threats to the quality of life.

In July 2022, the Government announced the Natural England-led Nutrient Mitigation Scheme. Part of this scheme aims to fast track the delivery of nutrient mitigation in affected areas of the country. One of the approaches advocated is the creation of new wetlands to 'soak up' or mitigate the impacts of nutrient pollution.

Natural England has worked with The Rivers Trust and The Constructed Wetland Association to produce the Wetland Mitigation Framework. The Framework is a high-level decision-support system to assist in the evaluation of wetland mitigation proposals which have been designed primarily to achieve sustainable improvements in water quality through nutrient reductions (with an emphasis on nitrogen (N) and phosphorus (P)). This **Detailed Design Guide** has been partly funded by Natural England as a companion to the Wetland Mitigation Framework guidance.

Types of wetlands

Wetlands come in many forms ranging from extensive peatlands to garden ponds and from seasonally inundated floodplains to agricultural ditches. The Detailed Design Guide is not intended for use to design all wetland types. The emphasis of the Detailed Design Guide is on treatment wetlands that have been designed specifically to integrate within their catchment for the purpose of mitigating the impacts of nutrients on the aquatic environment.

The focus of the Detailed Design Guide is on wetlands that can remove nutrients. However, wetlands generally will do much more than simply remove nutrients. The design and creation of wetlands offers the opportunity to address nutrient issues as well as to provide wider benefits for society. Traditionally, constructed or treatment wetlands have been designed to address a range of pollutants, not just nutrients.

Treatment wetlands have a role to play in the restoration and improvement of the natural functions of a catchment and the provision of ecosystem services. However, they may also hinder wider catchment restoration objectives if their design is not fully integrated. Similarly, they can impact floodplain function, ecological networks or carbon sequestration if appropriate consideration of wider issues is not addressed in the design process.

To understand better the different types of wetlands that can be created, it is helpful to consider wetlands within the context of achieving their objectives within the scope of Nutrient Mitigation Schemes along with the traditional main types of treatment wetlands.

Wetlands within the context of nutrient mitigation

Wetlands have a critical role to play in mitigating nutrient impacts on the water environment but also in wider environmental improvements both in aquatic habitats and in the broader restoration of catchments. For the purpose of this Detailed Design Guide, three main categories of wetland have been defined:

- Quantified nutrient removal
- Unquantified nutrient removal
- Catchment Restoration Wetlands

Quantified nutrient removal wetlands

A defined amount of nutrient removal is the focus of quantified nutrient removal wetlands. These wetlands are designed, created and managed to deliver an expected amount of nutrient to be removed over a given time. They are sometimes referred to as nutrient mitigation wetlands. Due to the desire to deliver on consistent and robust water quality standards over time, they can also be referred to as quantified nutrient removal wetlands.

Their primary design criterion is nutrient mitigation but, through sensitive design processes, they can still deliver wider benefits. The operation and performance will be expressed in terms of Kilograms of Total Nitrogen or Phosphorus removed per year. The calculations used in the design of these wetlands and the prediction of future performance should be suitably precautionary and adhere to the Wetland Mitigation Framework. Hydrological isolation of the wetland system from any groundwater sources is required for accurate quantification of nutrient removal. This type of wetland aims to avoid further deterioration of the environment and can deliver reductions to offset excess nutrient impacts from new or existing development and wastewater treatment works, or for Catchment Nutrient Balancing (CNB) schemes, ensuring there is no net increase in nutrients within the receiving environment. Such wetlands can be designed under processes such as Nutrient Neutrality or Environment Agency permitting. Under these applications the nutrient reduction will need to be quantified and offset with certainty over time.

Unquantified nutrient removal wetlands

The primary objective of unquantified nutrient removal wetlands is to reduce nutrients, but it is not possible to predict or quantify the amount accurately or with certainty over time. These wetlands can be intended to reduce nutrient levels and improve water quality towards required target levels, but nutrient credits can only be earnt based on post construction and operation monitoring. The reduction in nutrients could be for the benefit of protected sites or wider environment under the Water Framework Directive. These reductions do not necessarily require quantifying with the same degree of certainty as quantified nutrient removal wetlands, however, wetlands designed to have nutrient removal as a secondary objective can still contribute to wider environmental restoration targets, and it can be helpful to have a broad understanding of their ability to mitigate nutrients. Additional outcomes may deliver other water quality benefits, such as removal of sediments, or wider ecosystem services, for example flood attenuation, educational opportunities, or biodiversity enhancements. Where possible, this type of wetlands will maximise secondary outcomes without impacting on the primary objective of removing nutrients.

Catchment restoration wetlands

Beyond the targeted quantified or unquantified removal of nutrients, wetland restoration has a role to play in the improvement of the natural functioning of a catchment and the provision of ecosystem services. This can include water quality enhancement or other improvements such as enhancing stream morphology or floodplain hydrological connection. Both Quantified and Unquantified Nutrient Removal Wetlands will contribute to catchment restoration through the removal of nutrients and the provision of ecosystem services. Optimising the ecosystem services provided by both types of wetlands will increase their contribution to catchment restoration. However, both these types of wetlands may also hinder wider catchment restoration objectives if their design is not fully integrated, and they impact floodplain function, ecological networks or carbon sequestration.

Traditional treatment wetland types

There is a significant amount of published literature on treatment or constructed wetlands. Six common or traditional types of wetlands are usually identified in the literature, for instance in Langergraber et al. (2020). The following notation can be used to describe treatment wetlands:

- Vertical Flow wetlands
- Horizontal Flow wetlands (with sub-surface water flow)
- Reactive media (Horizontal and Vertical) wetlands
- Free Water Surface wetlands
- Floating Rafts
- Floodplain reconnection & other ‘natural’ wetlands

Nearly all treatment wetlands will improve water quality through the removal of nutrients. However, not all treatment wetlands will optimise the conditions required for removing nutrients. Similarly, different treatment wetlands will remove Nitrogen and Phosphorus at different rates. Furthermore, without appropriate management, some treatment wetlands may ultimately become potential nutrient sources. A treatment wetland that is good at removing Nitrogen may not be as good at removing Phosphorus and vice versa. This is primarily as a result of different processes that change, store and remove nutrients and the environmental conditions required to drive these processes.

A robust framework for designing treatment wetlands to achieve particular water quality objectives is defined in Langergraber et al. (2020), This approach sets out the following steps (similar steps are emphasised in the Wetland Mitigation Framework):

1. Define the treatment objective(s) (for instance, is a quantified amount of Nitrogen reduction over time required or is betterment the desired objective?).
2. Define the processes required to reach the treatment objective (for instance, how is nitrogen or phosphorus going to be managed within the wetland?).
3. Choose the appropriate treatment wetland type, or a combination of different types, that will deliver the treatment objective.

An introduction to wetland nutrient processes

The conditions that occur in wetland soils are due to the presence of water at or near the ground surface. These unique hydrological conditions influence the prevailing biogeochemical processes, the combination of chemical transformations and transport processes absent in other ecosystems.

Wetland soils are characteristically waterlogged or flooded resulting in oxygen-depleted, reduced or anaerobic conditions but they can also retain a narrow, oxidised surface layer within which processes requiring oxygen, or aerobic conditions, can occur. Transformations of nitrogen and phosphorus, along with other chemicals such as iron, manganese and carbon, will operate in and across these anaerobic and aerobic zones.

The chemical transformations and transport processes will also depend on:

- the variability or stability of the hydrology
- the supply of chemicals from outside the wetland (such as the input of treated effluent)
- the prevailing environmental conditions (such as rainfall and temperature)
- the soil properties
- the plants within the wetland.

Informative reviews of the nutrient transformations present in treatment wetlands are provided in Mitsch and Gosselink (2015) and in Kadlec and Wallace (2008).

The following describe the main processes that deliver the removal of nutrients within treatment wetlands.

Filtration: This is a physical process that depends on the transport of water through a filter. As water moves through a filter medium, such as soil, sand or gravel particulate matter is filtered out and trapped within the filter.

Sedimentation: This is perhaps the easiest wetland process to conceptualise, sedimentation comprises trapping suspended solid particles in the incoming water, either by settlement, or by interception and “filtration” by wetland plants and dead plant matter. In many cases these solid particles will contain elevated phosphorus concentrations, so trapping these solids can also reduce phosphorus loads, at least temporarily. Phosphorus processing in wetlands is complex, and the phosphorus contained within incoming sediment may be released back into the wetland ecosystem, however a proportion of the phosphorus load can become buried and accreted as wetland soils.

Nitrification: Ammonium (normally in wastewater) may be converted into oxidised forms of nitrogen in a highly aerobic wetland environment. A very efficient method for doing this is a pulse-loaded vertical flow wetland. Availability of oxygen is often the limiting factor in the rate of nitrification, so aerobic wetlands may be a useful pre-treatment step if dealing with high strength wastewater such as domestic wastewater or contaminated farmyard runoff. Overall nitrogen load will, in general, not be significantly reduced by highly aerobic wetland environments until the oxidised forms of nitrogen that are produced can be removed by “denitrification” processes. Nitrification is an autotrophic process that means that the energy for bacterial growth is derived from the oxidation of nitrogen compounds, primarily ammonia, where alkalinity is sufficient.

Denitrification after nitrification: The removal of nitrogen by biological nitrification and denitrification is a two-step process. In the first step (nitrification), ammonia is converted under aerobic conditions to nitrate. In the second step (denitrification), nitrates are converted to nitrous oxide (N_2O) or nitrogen gas (N_2) under oxygen depleted (anoxic) conditions where there is sufficient carbon available to provide an energy source for denitrifying bacteria.

Adsorption: This is a surface process that results in the transfer of a molecule from a fluid onto a solid surface. This is the result of physical forces or chemical bonds. Often the process can be reversed with temporarily bound substances being released back into the fluid. For phosphorus, adsorption involves soluble inorganic phosphorus moving from the pores in the soil media to the soil particle surface. Normally, with increased clay, iron or aluminium content the soils adsorption qualities increase.

Adsorption of phosphorus can be important in the start-up phase of a treatment wetland system, particularly on clay or iron rich soils. However, it is possible that adsorption of phosphorus will not be sustained over extended periods unless a method of introducing

new material, such as sediment, to sustainably supply new surface adsorption sites, can be devised.

There are several “passive” treatment systems commercially available which make use of specially designed ‘reactive’ media with a very high capacity to adsorb or precipitate phosphorus. Such treatment systems may also be planted with wetland plants and function like a wetland but are often isolated in their environment and not integrated within the wider landscape. Some of these reactive media may have a role to play in intensifying phosphorus removal rates where land is constrained, however, the inclusion of such media within treatment wetlands may not represent a sustainable practice as the media may require intermittent replacement to sustain the desired processes; the phosphorus-saturated media will need to be appropriately disposed of; and the opportunity for the system to be sustained over a period of years through natural processes is unlikely to occur. Furthermore, the environmental costs and benefits of the media production, replacement and recycling/ disposal will need to be carefully considered in the sustainability aspects of the design process.

Precipitation: This process involves converting elements, such as phosphorus, to insoluble forms and their adsorption on surface, usually the soils or substrates within a treatment wetland.

Plant uptake: Plants (along with algae and bacteria) uptake nutrients, through transpiration, by drawing water from wetland soils and from the water column through root interception, mass flow, and diffusion. Often the uptake of nutrients represents a temporary or seasonal store as the nutrients can be released back into the water column as the plant litter degrades.

Selecting the most appropriate treatment wetland

The table below (adapted from information included in Langergraber et al. (2020) and supplemented with best professional opinion) summarises the effectiveness of three common treatment wetlands in performing a range of processes. It is clear that the effectiveness of the different treatment wetlands varies depending on the process under consideration. For nutrient removal, a well-designed and managed Free Water Surface (FWS) wetland provides the most consistent process performance. Reduction in overall nutrient concentration will generally not be achieved in other forms of wetland in a sustainable way (i.e. sustained over a period of many years by natural processes alone). A critical factor in the success of FWS wetlands in transforming and removing nutrients is the maintenance of relatively stable anaerobic and aerobic conditions associated with shallow water (less than 0.3m) planted with dense emergent vegetation.

Objective	Removal of solids		Removal of dissolved organic matter		Removal of ammonia		Removal of nitrogen		Removal of phosphorus			Removal of microbial contamination	Removal of organic micropollutants		Removal of metals		
Key processes	Filtra.	Sediment.	Aerobic degradation	Anaerobic degradation	Nitrification	Adsorp.	Denitrification after nitrification	Plant uptake	Adsorp.	Precip.	Plant uptake	Filtra.	Biological degradation	Adsorp.	Sorption	Plant uptake	Precip.
VF Wetlands	++		++		++	+			+			++	++	+	+		
HF Wetlands	++		+	++		+	+		+	+	+	++	++	+	+		
FWS Wetlands	+	++	+	+	+		+	+	+	+	+	++	+			+	+

Table 1.1. Key processes controlling the transformation and removal of contaminants in treatment wetlands (Nutrient processes highlighted in pale green cells; VF – Vertical flow; HF – Horizontal (sub-surface) flow; FWS – Free Water Surface; ++ a significant process of the treatment wetland; + a minor process of the treatment wetland; blank – the process is unlikely to significant in the treatment wetland).

Objective of the Detailed Design Guide

This Detailed Design Guide therefore focusses on Free Water Surface (FWS) wetlands and how to estimate the rate of phosphorus and nitrogen reduction and design robust systems that will sustainably function over considerable time periods. The table above can be used to identify the key processes that exist in the three most common wetland types.

Limitations of the guidance

The emphasis within the Detailed Design Guide is on establishing FWS wetlands for nutrient removal. However, different wetland types, including FWS wetlands, can improve other water quality parameters, such as metals, pathogens and solids. There is a considerable suite of guidance already available for the design and management of other treatment wetlands and their role in reducing other contaminants. The table below signposts the other published guidance currently available.

Wetland Types	Contaminants considered	Source
Farm wetlands (including VF, HF and FWS wetlands)	Nitrates, ammonia, phosphorus, sediment, agrochemicals, microbial pathogens	MacKENZIE, S.M. and McILWRAITH, C.I. 2015. Constructed Farm Wetlands. Wildfowl & Wetlands Trust, Slimbridge, UK. https://www.wwt.org.uk/our-work/wetland-conservation-unit/resources/constructed-farm-wetlands/
Constructed farm wetlands (FWS wetlands)	Nitrates, ammonia, phosphorus, sediment,	https://www.sepa.org.uk/media/131412/constructed-farm-wetlands-manual.pdf
Small scale VF wetlands for domestic properties	Domestic septic tank effluent, ammonia, BOD	https://constructedwetland.co.uk/media/file_uploads/CWA_Design_Guidelines_v10.pdf
Integrated Constructed Wetlands (FWS wetlands)	Nitrates, ammonia, phosphorus, sediment, agrochemicals, microbial pathogens	https://www.gov.ie/en/publication/68a26-integrated-constructed-wetlands-guidance-document-for-farmyard-soiled-water-and-domestic-wastewater-applications/

Table 1.2. Location of other wetland detailed design guidance

Design objectives

Background

Wetlands can be designed, created and managed for a variety of objectives. Appropriate wetland design to target the specific removal of nutrients requires clearly defined objectives, i.e. what is the wetland designed to achieve? Wetland design objectives often relate to a water quality parameter, such as a desired reduction in nitrate concentration, the removal of a total phosphorus load or the need to reduce suspended solids content below a particular criterion. Often for nutrients, this will be expressed as a reduction in the overall load of a parameter, such as kilograms of total nitrogen being removed by the wetland. However, every wetland provides the opportunity to deliver additional benefits beyond nutrient mitigation. Consequently, there may be other considerations within the design objectives, for instance the potential to provide wider benefits to society (sometimes referred to as ecosystem services or natural capital benefits) such as through reducing flood risk, providing a habitat for pollinators or enhancing recreational or educational opportunities.

For all wetland systems that are being considered in the context of providing nutrient mitigation (i.e. the wetland will reduce nutrients with certainty, satisfying a Habitat Regulations Assessment), it is necessary to clearly articulate what the wetland intends to achieve in terms of nutrient reduction. ***However, where a wetland is not being considered within the context of the Habitat Regulations or a permit limit, the degree of scientific certainty and the precautionary approach applied can be less rigorous***.

Defining the objectives in terms of specific nutrient reductions requires a robust understanding of several factors. Usually within the context of nutrient neutrality and the Habitat Regulations, the focus will be on understanding the amount (as a mass in kilograms) of a substance (typically Total Phosphorus or Total Nitrogen) removed by a wetland over a year (usually termed the load – see Box 1),whereas wetlands that are designed to achieve a water quality discharge permit limit will focus on delivering a specified concentration in the water leaving the wetland. Design objectives should consider several factors including the source of the water entering the wetland, how much water will be flowing into the wetland, the concentration of the substance in the inflowing water, how concentrations and flows might vary over time, for instance during different seasons, and the level of confidence there is in the understanding of these factors.

Design objectives for treatment wetlands for nutrient mitigation, or those that need to meet specific permits limits, will require a higher level of confidence in the baseline data than wetlands being delivered for other reasons.

BOX 1 Understanding loads

The load is the total amount of a substance, such as total phosphorus (TP), that will be received by the wetland over a defined period of time. The load is derived from combining the amount of water entering the wetland (the discharge – sometimes incorrectly termed the "flow" and sometimes incorrectly termed the volumetric flow rate) over a fixed time period and the concentration of the substance in a fixed volume of water, usually a litre (L). Calculating the load is demonstrated in the example below.

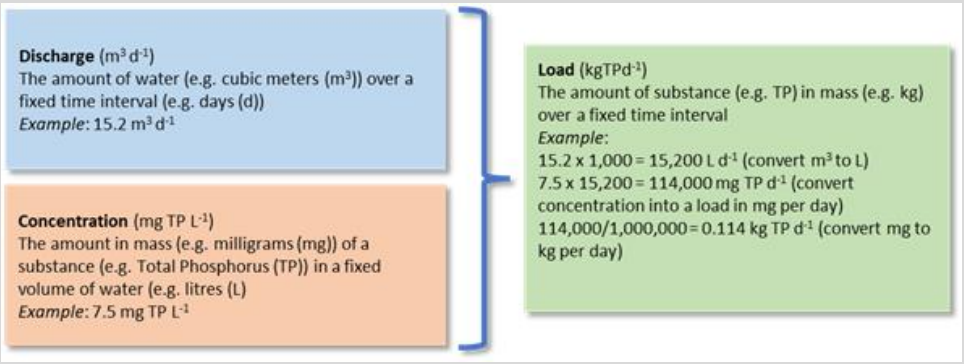


Figure 2.1 Summary of loads and concentrations

**NB "Discharge" is a technical term in hydrology that refers to the flow rate of water through any line across a hydrological system, (not to be confused with "Final Discharge" or "Final Effluent" from a treatment system"*

Characterising the wetland influent

A fundamental design objective is to define the **source of water** that will be treated by the wetland (the 'influent'). Consideration needs to be given to:

- Wetlands can treat water from a variety of different water sources. These include (but are not limited to): septic tanks and package treatment plants; municipal wastewater treatment works; combined sewer overflows (storm water); rural or urban drainage; runoff from fields; groundwater and polluted water from rivers or streams. When designing a wetland, it is important to define the characteristics and quantities of influent water to estimate the incoming load of nutrient, and to ensure the hydrological controls within the wetland are appropriate.
- Some wetland sources such as from septic tanks and package treatment plants may have a very well-defined source of water, which is relatively consistent from day-to-day and subject to well-researched industry standards on which to estimate flows and loads. Often such systems have been subjected to rigorous laboratory analysis and will have associated performance certification.
- Water derived from more 'open' systems, such as that generated from agricultural run-off from fields, ditches or farmyards, or urban drainage from roads and other hard surfaces will be influenced by rainfall, so the wetland influent is liable to possess wider

variations in flow and concentration. It is important to clearly understand the size of the catchment of the drainage system that is to be treated, and the nature of the ground cover (proportion of soft landscaping and other land use types) and the soil types in the catchment to derive a meaningful estimate of the potential flow of water into a wetland. The influence of climate change on the flows to the wetland from open systems also requires evaluation to future-proof the wetland. Runoff quality may be influenced over time by factors such as changes in agricultural practices, such as arable cover, fertiliser application rates or long-term land use change.

- Water from river systems which has been diverted to a wetland and groundwater discharges will require detailed hydrological or hydrogeological modelling, or else an extended monitoring period to understand flows and loads sufficiently. Again, the implications of changes within the surface or groundwater catchments and the impacts of climate change need careful consideration to appropriately characterise the wetland influent.
- Isolating a wetland from groundwater is important when quantifying the nutrient removal potential accurately as these externalities (groundwater intrusions/losses) are highly challenging to quantify reliably within a modelled approach.
- Groundwater can be particularly difficult to characterise. Although water quality tends to be less variable than from other sources there can be long term trends which could have a significant impact on treatment. Groundwater responds to land use and land management decisions taken many years ago. Typically, water percolates at about 1m per year through the unsaturated zone which means that current water quality is often representative of conditions within the catchment from decades before.
- Municipal wastewater treatment systems and CSOs typically receive water from combined sewers that receive inflows of domestic effluent, trade effluent, surface water runoff (from rain) and infiltration from groundwater and misconnections within the sewerage system. The human population and the characteristics of the surface water catchment may well change over time. As such the flow and load variation is likely to be complex, though it may be relatively well understood by the water company. Flows and loads at any point in the network will generally be forecast using a complex network model, which needs to be calibrated at regular intervals to ensure its accuracy. It is also considered to be best practice to verify any modelling approach with *in situ* monitoring and data collection.
- The source of the water being treated by a wetland will influence the choice of wetland, the design process and the final design.
- If the source of water has not been characterised robustly, both in terms of the amount of water (the flow) and the water quality parameters (usually as a concentration or load) the overall design process will be undermined. Some sources are more difficult to characterise than others due to the difficulty in collecting representative data. Where the characterisation of the source of the influent is challenging, a precautionary approach should be adopted with regards to defining the nutrient removal potential of a wetland.

Once the source of the water to be treated by the wetland is defined, it is necessary to consider the quality of the water to be treated. The **quality of the water** to be received by the wetland is critical to how the wetland will function and the type of wetland required to treat it. The quality of the wetland influent needs to consider:

- The quality of the water entering the wetland needs to be characterised. It is possible that the confidence assigned to the characterisation of the quality of the water entering the wetland will depend on the nature of the source. Where confidence is low a precautionary approach should be applied. The characterisation of water quality can be based on different information sources including *inter alia*:
    - empirical data which is representative of inflow to the wetland over a time period;
    - surrogate data derived from modelling using best-practice approaches and industry standard methods including, where appropriately selected, published Nutrient Neutrality calculators;
    - surrogate data based on data drawn from relevant peer-reviewed literature sources that are appropriate to characterise the inflow; and
    - surrogate estimates based on generic values derived from a range of sources.
- The characterisation of the water quality should review temporal variation (within year and over a period of several years) to ensure that the range of conditions that the wetland will experience is known.
- The characterisation should consider the most up to date and relevant information on influent water quality.
- For the purposes of nutrient neutrality calculations, it is the nutrient content (primarily nitrogen (N) and phosphorus (P)) that will be of interest, though wetlands may be used to treat other parameters (such as sediment, biochemical oxygen demand, heavy metals, pathogens, etc.). Appropriate information is needed on each parameter that the wetland is being designed to treat. Consideration should also be given to potentially limiting factors that could influence the removal of nutrients, such as pH, alkalinity or carbon.
- The water quality is usually characterised as a concentration, but other descriptors may be appropriate depending on the parameter being considered.

The volume of water entering the wetland is a critical consideration. ‘Closed’ systems, such as single dwelling septic tanks will usually have a regular inflow that will demonstrate predictable variation from month to month. However, more ‘open’ systems, such as those from rural or urban surface water drainage may demonstrate a significant variation in volumes entering the wetland, both from month to month and from year to year. Therefore, the following need to be considered when defining the **quantity of the water** to be treated:

- The flows need to be clearly characterised and all possible water sources, such as precipitation, groundwater, surface water and influent flow need to be considered and discounted if negligible. The confidence levels applied to the possible variations in flow over time, from all water sources, also needs to be understood and calculated.

- The calculation of water flows entering a treatment wetland can be based on different information sources. Different data sources will have different levels of confidence in their reliability and relevance. Consideration of the confidence in the information needs to part of the characterisation of the definition of the quantity of influent. The quantity of water to enter the wetland can include *inter alia*:
    - design flows e.g. from pumped or hydraulically controlled inputs;
    - empirical data collected at the point of inflow to the wetland over a time period;
    - surrogate data derived from modelling using best practice approaches and industry standard methods and estimations;
    - surrogate data based on data drawn from relevant peer-reviewed literature sources that are appropriate to characterise the inflow.
- The characterisation of the inflows to the wetland should include temporal variation (within year and over a period of several years) to ensure that the range of conditions that the wetland will experience is known.
- Ideally the most up to date and relevant information on influent water quantity should be used.

Defining the long-term trends in influent water quality and hydrological flows

The quantity of a pollutant that a wetland can remove is clearly dependent upon the quantity of the pollutant that will flow into the wetland over its design life. It is therefore important that the incoming flows and loads are considered not just at the time of the design process, but over the lifetime of the wetland. This design life should be clearly set out in design objectives, along with any “end of life” plans for the wetland. Consideration needs to be given to:

- Future increase or decreases in the design concentration or flow should be accounted for in the design and the forecast of pollutant removal. These should consider climate change as well as possible land use or population size changes. However, designs can only be based on current knowledge, so monitoring and, where possible, subsequent adaptive management should be planned to manage future changes in flow or concentration and the limitations these may impose on the system.
- As discussed above, confidence in predicted pollutant removal depends on the design and maintenance approach used and the level of available data on water flow and quality. Designs based on industry standard calculation will have higher confidence than those which use other approaches. The level of data on input water flows and quality will also impact confidence in the calculations. The confidence in the predictions can be increased by using the most conservative estimates. However, the application of water industry standards should be approached with caution and wherever possible verified by in situ monitoring results.
- Wetlands that receive water and nutrients from a larger catchment will tend to be more robust to small changes in land use and hydrology over the lifetime of the wetland than will wetlands that receive water from a very small catchment (such as a small

field or runoff from farm buildings). Conversely, small, clearly defined catchments which provide the source of water for a wetland may be easier to manage and to control in terms of land use and hydrology. Both these scenarios need to be considered in the characterisation of the potential long-term variability of the influent.

- Higher confidence, in water quality treatment, may be achieved for wetlands which have been significantly oversized potentially reducing the risks associated with underperformance. However, the implications of evapotranspiration over a larger wetland need to be fully understood.

Final water quality

The wetland should be designed to achieve a consistent quality of water leaving it. It is normal for the reduction of nutrients achieved by passing water through a wetland to be expressed as a reduction in load in kilograms of nutrient per year. The prediction of the quality of water leaving the wetland will depend on the characterisation of quality and quantity of water flowing into the wetland and the design and management of the wetland. The predicted quality of water leaving the wetland should be derived from a robust design process, and appropriate methodologies which are discussed in following sections.

- Confidence levels in the predicted water quality leaving the wetland are highly dependent on the confidence levels in the water quality and quantity data entering the system.
- For all nutrient mitigation or permit limit driven wetlands, it is important to have high confidence levels in the water quality and quantity entering the wetland and therefore high confidence levels in the predicted water quality exiting the wetland. However, for treatment wetlands that are not being considered within the context of the Habitat Regulations or a permit limit then confidence levels in the water quality and quantity data may not need to be as high and broader assumptions regarding the level of treatment can often be made.

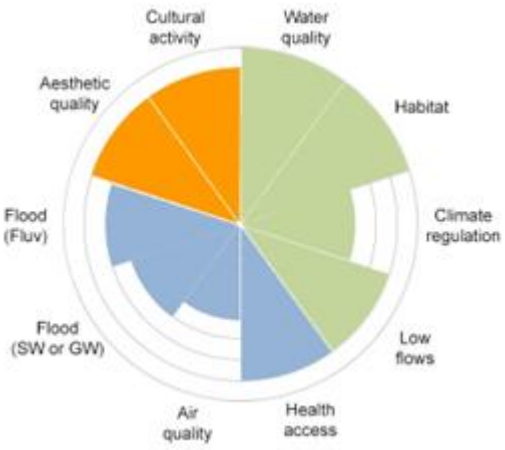
Designing in multiple benefits

Whilst a wetland designed to improve water quality may be considered by some to represent a single end of pipe solution for water quality treatment, the wetland will still provide other benefits to society even if these have not been considered explicitly in the design and development process.

- Wherever possible, efforts should be made to consider a wetland as natural capital which can deliver multiple benefits to people which extend beyond a limited subset of benefits. Therefore, all designers are encouraged to maximise the multiple benefits a wetland can provide. Through appropriate consideration in the design process, treatment wetlands can provide a wide range of environmental, social and cultural

benefits across all ecosystem services (see benefits wheel for common benefits, Figure 2.2).

Free Water Surface wetland



Horizontal Flow sub-surface flow wetland

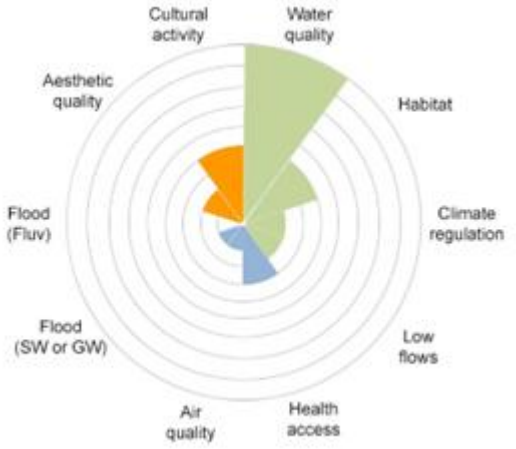


Figure 2.2. Benefit wheels

For each treatment wetland the common benefits which they could provide have been summarised using a wheel which covers 10 benefit indicators that have been ranked (based on expert review and published literature) on a scale from 1 to 10 to give an indication of the relative contribution the treatment wetland can make to the provision of a certain benefit. Benefit type: Environmental Social Cultural

If well designed and explicit links are made between the wetland and actual beneficiaries, Free Water Surface wetlands can also provide the following benefits in addition to the ones identified in Figure 2.2:

- Freshwater (e.g. for irrigation)
- Food (e.g. crops, fruit, fish etc.)
- Fibre and fuel (e.g. timber, plant fibres, sphagnum etc.)
- Genetic resources (used for crop/stock breeding and technology)
- Biochemicals, natural medicines, pharmaceuticals
- Ornamental resources (e.g. flowers etc.)
- Energy harvesting (e.g. biofuels)
- Pest regulation (e.g. providing habitat for species that predate pests)
- Disease regulation (e.g. provide habitat for bacteria that predate pathogens)
- Erosion regulation (e.g. slowing flows reducing erosive power)
- Pollination (e.g. habitat support populations of pollinating organisms)
- Fire hazard regulation (e.g. wetland habitats act as fire breaks)
- Recreation and tourism (e.g. provides visitor attraction or recreation areas)
- Social relations (e.g. fishing, grazing, art, nature group communities)
- Education and research (e.g. supports informal and formal learning and research)

Benefits are only realised by society if people have access either directly or indirectly to them. Consultation with potential beneficiaries and providing access are key aspects of a successful design. When considering any cost-benefit analysis for the treatment wetland, it is important that all benefits are recognised, captured and included. Failure to do so results in externalities remaining and the actual value of the treatment wetland being underestimated.

Benefit examples

The following provide a snapshot of some of the benefits that treatment wetlands can provide beyond improvements in water quality:

- Current global warming potential of treatment wetlands is generally small when compared with greenhouse gas emissions from agricultural activities and/or traditional wastewater treatment processes (Mander et al. 2014).
- Wetlands can reduce summer air temperatures through a cooling effect by 1-3^{o}C (Zhang et al. 2022).
- Treatment wetlands can offer a cost-effective and efficient solution for stormwater management in the UK compared with traditional water management facilities (Lucas et al. 2015).
- Treatment wetlands provide habitat and refugia for many species enhancing local biodiversity particularly in urban or agricultural landscapes (Agaton & Caparas Guila 2023).
- Agricultural benefits come from the potential reuse of wastewater from treatment wetlands, considering it as an ‘extra’ income for avoided losses on production due to drought events equal to 20% on gross saleable production (Garcia-Herrero et al. 2022).
- People can benefit from an ecosystem’s aesthetic and recreational components, which include physical, mental, and emotional well-being benefits (Germandi et al. 2015).

Sustainability

Treatment wetlands provide the opportunity to develop sustainable solutions for water quality management, but key design principles should be followed to ensure that sustainability is realised. Failure to do so usually results in higher capital and operational costs and greater whole life cycle carbon costs. Durability, energy efficiency, resource minimisation, use of sustainable materials and native plants need to be considered within any design and will be discussed in detail in subsequent sections.

It is important that sustainability is considered over the lifetime of the treatment wetland including construction, operation and potential decommissioning of the wetland in the future.

Durability: A treatment wetland should be constructed with robust materials so significant repairs to the wetland cells, such as re-installation of a damaged liner. and replacements of infrastructure, such as pipework, are avoided or kept to a minimum for the lifetime of the wetland which can be more than 100 years.

Energy efficiency: Construction and decommissioning – treatment wetlands should be designed to fit within the natural contours of the landscape so soil movements and waste management can be kept to a minimum to minimise the energy requirements during construction. Designers should also consider decommissioning and design wetlands so that the energy required to decommission is minimised.

Energy efficiency: Operation - ideally a treatment wetland is designed to avoid any energy requirement for the operation of the system. This can be achieved if the water entering the wetland does so via gravity. If water has to be pumped, then the power source should come via solar panels or wind pumps. Thought should also be given to routine operations such as vegetation cutting and clearance, and desilting. The treatment wetland should be designed so these operations can be kept to a minimum and waste disposal is as close to the wetland as possible to avoid transport energy costs.

Resource minimisation: Potentially the requirement for liners, aggregates and infrastructure for the construction of treatment wetlands can involve significant use of resources and result in a large carbon footprint. Treatment wetland designs should avoid, where possible, the use of artificial liners, particularly when there is an option for site won clay, should minimise the use of aggregates and use site won soils, and ensure that infrastructure is kept to a minimum, for example, favouring open channels rather than pipework for water distribution.

Sustainable materials: Every effort should be made not to ‘over-engineer’ the treatment wetland. The use of concrete, steel and other manufactured materials should always be challenged to understand whether there is a more sustainable option which provides the same function and level of robustness but with a lower carbon footprint. Where artificial or synthetic liners, planting mediums and infrastructure are unavoidable, within the design of a treatment wetland, it is important that the most sustainable and low-carbon products are selected when specifying materials to be used. The use of products such as concrete, oil-based products such as plastic or artificial liners should be avoided wherever possible. It is good practice to undertake a whole lifecycle carbon footprint analysis of the materials being specified to ensure the carbon footprint of the project is kept to a minimum.

Native plants: Plant species specified for a treatment wetland should always be native species of local provenance. Ideally, they should be designed to mimic plant communities found within the local area. It is essential that any plants introduced into the treatment wetland are screened for possible alien invasive species.

Checklist – setting design objectives

The following provides a checklist of the critical path required to guide a designer through setting clear objectives for the design of a treatment wetland.

The recommended approach to setting the design objectives is as follows:

1. Fully characterise the quantity and quality of the water to be received by the treatment wetland.
2. Define the treatment objective(s). With regards to quantified nutrient removal wetlands, this should ideally be in terms of a reduction in nutrient load expressed as kilograms of nitrogen or phosphorus removed per year.
3. Evaluate the processes required to reach the treatment objective.
4. Select the appropriate treatment wetland type, or a combination of different types, that allows the design to reach the treatment objective. The focus of this Detailed Design Guide is on Free Water Surface wetlands as these provide both the most suitable conditions for the majority of nutrient removal processes and they have the potential to deliver the greatest additional benefits to society.
5. Establish an inclusive approach to identify and integrate wider benefits into the design objectives.

Feasibility and outline design process

Introduction

The design objectives should articulate what the treatment wetland is expected to achieve. However, before a wetland is designed in detail, there are many items that need to be assessed as part of a feasibility study and each one of the factors below needs to be examined before detailed design can be started. The Constructed Wetland Hub has been developed to assist this process. Where data is available in the Hub this is noted in each section, alternatively different sources are indicated with links where available. A full list of data available to support feasibility can be found in 'Data availability summary', towards the end of this section. For many of the factors considered as part of the feasibility process there may be appropriate mitigation strategies to overcome potential constraints. If the risk associated with one of the issues identified below is not assessed, or if a risk that is identified is not mitigated, then the design could potentially be flawed. There are some scenarios where specific items of key data are not required, these are highlighted in the text. Optional information is also identified which should be incorporated if it is available. The inclusion of optional information indicates that the design is well conceived and therefore low risk, both to the regulator and the delivery organisation. Data from this process will be used in the Design Stage Risk assessment that is an integral part of the Construction, Design and Management process.

Calculating the required wetland area

The feasibility work aims to evaluate whether it is possible to establish a wetland that will be able to meet the design objectives and fit within the available land constraints. The first factor to consider, the area that the treatment wetland will cover, can be approached from two scenarios:

1. An area of land of a predefined dimension (in hectares or square meters) is available to use for the creation of the treatment wetland; or
2. The imperative is to achieve a defined nutrient load reduction or outlet concentration and the treatment wetland needs to be of the required area to achieve this design objective.

Under scenario 1 above, the sizing of the wetland, and therefore its nutrient removal potential, is dictated by the land available and an appraisal of any constraints that might be present within the available land. Under scenario 2, the wetland has to be as small or large as is required for it to meet its nutrient removal objectives.

Failure to understand the implications of the size of the treatment wetland that will be delivered undermines the efficacy of the feasibility assessment.

Wetland sizing calculations

The review of the literature and the knowledge of industry best-practices highlights the application of the three following approaches to calculate nutrient reductions and to estimate wetland area:

- The P-k-C* model.
- A ‘plug flow’ model termed the k-C* approach; or
- Regression (or exponential decay) equations;

P-k-C* model

The P-k-C* model described in Kadlec and Wallace (2008) is considered to be the most robust approach and is strongly recommended for calculating the wetland area. This model is a ‘First Order’ reaction model. That is to say, the rate of reaction (the nutrient removal processes) assumed is dependent upon the concentration of the parameter in question, Hydraulic Retention Time and Temperature. Such a model can be parameterised either to derive a treatment area based upon target performance (load removal or outlet concentration), or else to derive the expected nutrient removal from a wetland with a particular treatment area.

The P-k-C* model considers the area of a wetland within the hydraulic loading rate (HLR). The parameters P, k and C* describe the way the contaminant of interest is processed within the wetland. C* is the ‘background concentration of a particular parameter, such as Total Nitrogen. The background concentration is a parameter that represents an irreducible concentration that will exist in the water in a wetland that results from internal biogeochemical processes i.e. the contaminant would be present without the addition of the influent. Therefore, it represents a concentration below which further removal of contaminant is impossible. k is the areal-based reaction rate coefficient, which describes the speed with which contaminants at any particular concentration (above C*) are removed from incoming water by the wetland. P is a parameter that describes both the hydraulic efficiency of the wetland, and the way in which contaminants ‘weather’ or breakdown as they pass through the wetland (if contaminants are actually a mix of chemicals (e.g. Total Nitrogen), some of those chemicals that go to make up Total Nitrogen will break down more readily than others).

Full details of the P-k-C* model can be found in Kadlec and Wallace (2008). The model equation is provided below:

$$A = \frac{PQ_i}{k_A}\left(\left(\frac{C_i - C^*}{C_o - C^*}\right)^{\frac{1}{P}} - 1\right)$$

Where

A = Area (m^2)
P = Apparent number of tanks in series (dimensionless)
Q_i = Influent volume (m^3/day)
k_A = Areal rate constant (m/yr)
C_i = Influent concentration (mg/l)
C_o = Outlet concentration (mg/l)
C^* = Background concentration (mg/l)

When approaching wetland sizing equations using the P-k-C* model, key model parameters such as the areal rate constant, are crucial in producing an accurate output

Although the P-k-C* model is robust for the determination of wetland sizing for tertiary phosphorus treatment following chemical dosing as supported by the literature (Lyu *et al.*, 2024) outside of these applications the model fit for phosphorus removal decreases, and as such a further precautionary approach should be taken.

For the design of nutrient removal wetlands a range of k values should be considered in line with the design objectives and risk profile of the project. This could include selecting a different value of k (30^{th} percentile instead of 50^{th} percentile) to have more confidence that the process area will be sufficient.

Further research is being carried out to allow for an improved P-k-C* model for P removal to support tertiary treatment without upstream targeted P removal and also secondary treatment applications. It is recommended that the most recent peer-reviewed data and information is consulted to ensure the application of the most robust k values.

Regression equations

There are numerous regression equations proposed in the literature to calculate the removal rates of different parameters, including Total Nitrogen and Total Phosphorus. The regression equations work on the principle that the removal of nutrients from a treatment represents an exponential decay curve with greater removal correlating to larger wetland area. Different equations will have limitations on their input and output range and the hydrological parameters used.

These regression equations should be used with caution as they can result in significant under or over estimation of the size of constructed wetland required for nutrient removal.

Caution regarding other sizing approaches

Any method of estimating nutrient removal and the associated wetland sizing that does not consider inlet concentration should be treated with caution and should be rejected unless

the approach is very carefully and robustly justified. Some potential pitfalls are considered below.

Percentage treatment efficiencies (for instance, the use of values derived from the literature such as 37% TN reduction, 46% TP reduction) should not be used to design a treatment wetland. These take no account of inlet concentration, flow rate or the size of the wetland so it is very rare that such estimates will be reliable. They may be a reliable way of predicting future performance of a wetland for which there is a lot of existing data, or for a wetland of the same size treating identical flows and loads.

Assumed areal removal rates (such as 1.2 gTP m^{-2} yr^{-1}, 93 gTN m^{-2} yr^{-1}) or similar hydraulic loading rates (HLR) as found in the literature (for instance in Land et al., 2016) should not be used. These take no account of inlet concentration, which will strongly influence the load removal in most wetland treatment systems. Such an approach can only work if the removal rates are derived from very similar situations with very similar inlet concentrations, in a directly comparable geographic location.

Sense checking results

Many wetland designers consider the mean nominal Hydraulic Retention Time as a sense-check for the design of treatment wetlands. Generally, a retention time in the range 8-24 hours is considered a ‘sensible’ or appropriate value. However, these values should be used only as a sense-check and not as the primary design approach. It is good practice to use two of the three approaches above to verify the results, however, the P-k-C* model should always be the primary approach used.

The choice of parameters used in all the models is extremely important. These need to be clearly articulated and described in relation to the context of the design site. The following issues should be considered and explained in the reporting of the sizing calculations:

- Parameter choice should reflect uncertainty regarding effective treatment area, temperature or wetland performance (where calibration data is poor).
- The design models and equations use rate constants (k, m d^{-1} or m yr^{-1}). The rate constants will vary for different contaminants, different climates and also for different wetland types.
- It is good practice to conduct sensitivity analysis on the choice of parameters chosen when calculating nutrient load removal using performance models. Greater scientific certainty can be applied to designs that have conducted sensitivity analysis and used conservative parameter values.
- Design calculations should be conducted for different seasons and potentially different influent conditions to understand and evaluate temporal variability in performance and to provide greater scientific certainty.
- The influence of climate change on the functioning of the treatment wetland needs to be factored into sizing calculations.

- Over time, more real-world data from nutrient removal wetlands in UK conditions will become available. When they become available these data should be used to validate and calibrate design parameters for future wetland proposals.
- The treatment area of a wetland should not be confused with the overall wetland footprint. The overall wetland footprint will include the treatment area (the functional area which will treat the water flowing through the wetland) and the larger area required to fit the wetland within its landscape. As a simple rule of thumb, the area around the functional treatment area may require an additional 20% to allow for access and management activities. However, this figure needs to be re-evaluated as the design develops and can only be precisely confirmed following completion of detailed design, plan and section specification drawings, cut and fill balances and integration of the solution into the site specific topography.

Wetland sizing and feasibility

Depending on the scenario being addressed (as described in scenario 1 and 2 above), it is possible that the desired area available for a treatment wetland may not be adequate to achieve the required amount of nutrient removal (under scenario 2 the calculated wetland area required to meet the design objectives is greater than the land available). The designer has to decide at this point the best course of action. This might be to revisit the design objectives, or it might require investigating the possibility of utilising additional land, if available.

Under scenario 1, the sizing calculations should indicate the nutrient removal potential of the area of land available for a treatment wetland. With this scenario, it is now necessary to assess the feasibility of utilising the land available and to understand any constraints that may be present.

Topography and levels

Design issue to be considered, mitigated and addressed?

- The topography of the site needs to be understood for a wetland to function properly, allowing water to flow through the system ideally under gravity and ensure that runoff from surrounding land does not flow into the wetland, hydraulically overloading the system and compromising the treatment efficacy of the design.
- Whilst the topography might constrain the ability to move water under gravity, pumped solutions may be possible. However, the sustainability of any pumped system needs to evaluate the type of pumps, their carbon footprint, the long-term management needs, power requirements, availability for remote sites and the viability of operation over the duration of the development.

- All wetland designs will require some earthworks. Balancing the amount of excavation with the amount of fill will minimise the cost of the design by minimising spoil arisings. The need for deep excavations should be avoided as these could cause health and safety issues and slope stability problems.
- Key water levels, which act as hydraulic controls for the wetland must be identified. The difference between the inlet and outlet levels determines the hydraulic head available to drive gravity flow through the system.
- The hydraulic head to drive flow through the wetland needs to be sufficient to achieve the design flows. The larger the plan area of the wetland the greater the hydraulic head that is required.
- The shape and layout of the wetland will determine whether flow is evenly distributed across the wetland. Poor design of wetland shape can lead to short circuiting of flow through a wetland cell which reduces the effective residence time in the cell and compromises treatment efficacy.
- Attempts should be made to work with the existing topography and to seek a congruous fit within the existing landscape.

Key information required for outline design

- A map showing the ground levels at the site of each of the proposed wetlands and the surrounding area.
- The anticipated invert level of the inlet to the wetland should be explicitly stated (in MAOD). This is particularly important for Treatment Wetlands downstream of conventional engineered sewage treatment works.
- The anticipated invert level of the outlet from the wetland, along with the water level in the receiving water, should be explicitly stated.
- Relative levels of top of batter, normal operating water levels and the media level base level at both the inlet and outlet should also be stated where possible.

Soils

Design issue to be considered, mitigated and addressed?

- Naturally functioning peat is an extremely valuable natural resource and should not be disturbed. It is likely that wetlands which require significant loss of peatland through excavation will be rejected by regulators and will increase the carbon footprint of the wetland.
- The hydraulic conductivity of the soil is required to estimate the vertical leakage from the wetland into the shallow sub-surface or deeper aquifer. Leakage can be an issue both in terms of treatment efficacy (if the wetland dries up) and water quality (if the receiving groundwater is sensitive – see below). Soil is highly heterogeneous and there is no substitute for a simple infiltration test.

- Contamination of surface or groundwater may be an issue if contamination in the soil is mobilised by flows through, or leakage from, the wetland.
- Nutrients in mineral soil may be mobilised by excavation and removal of vegetation and lost to the wider environment. This will be a temporary issue but should be accounted for in the design or the commissioning of the wetland and in the nutrient balance for the wetland. Check the Constructed Wetland Hub to identify historic land use and test the soil if it is likely to have high nutrients.
- Degraded peat soils may be a significant source of nutrient and greenhouse gases for a period following rewetting. In the longer term it is likely that these issues may be outweighed by the benefits of restoring a healthier peatland system.

Key information required for outline design

- A map of the expected soil type for the site. It should be noted that landscapes are highly heterogeneous and as such this map will only give an indication of soil type and properties.
- A simple site investigation identifying the local soil type along with an estimate of hydraulic conductivity. The site investigation should also be used to identify if contamination is present so that this can be factored into the assessment.

Geology and hydrogeology

Design issue to be considered, mitigated and addressed?

- The shallow geology of the site is important because it provides some (if not all) of the parent material for the media to be used within the wetland formation and determines the vulnerability of any groundwater below the site.
- If the drift or solid geology is also an aquifer it could provide upward discharge of groundwater into the wetland which could compromise the treatment efficacy of the wetland.
- If the drift or solid geology is an aquifer, which is being used to supply potable water or provides inflow to a sensitive natural system (spring or existing wetland), leakage from the wetland could reach the receiving groundwater, and the risk of pollution should be assessed, see Groundwater protection below.
- If there is an upwards head gradient in the groundwater, the viability of a liner and/or the ability to maintain hydrological control in the wetland needs to be understood to ensure that the functioning of the wetland is not compromised.
- The design water level in the wetland relative to the hydraulic head in the groundwater determines whether the wetland will receive or discharge water from or into the aquifer.
- In some circumstances, where the geology is complex or highly heterogenous, a site investigation identifying the local drift and solid geology properties and the

presence/absence of fissures or fractures may be the only way to accurately characterise the geological risk at the site.

Key information required for outline design

- A map of the expected drift geology type for the site. It should be noted that drift properties are highly heterogeneous and as such this map will only give an indication of drift type, thickness and properties. The map should also include the stipple layer from the groundwater vulnerability maps, to give an indication of the thickness of the drift deposits.
- A map of the expected solid geology and hydrogeology below the site. Additional information can be gathered from BH logs if these are available for a location near the site - these can be accessed from GeoIndex - British Geological Survey (bgs.ac.uk).
- A site investigation which may be available if there are significant engineering works nearby e.g. a sewage treatment works and is the most reliable source of geological/hydrogeological data.

Groundwater protection

Design issue to be considered, mitigated and addressed?

- If a wetland is receiving a source of water that has higher contaminant levels than are generally prevalent in the surrounding environment (e.g. discharge from a wastewater treatment works) it is important to be sure that the water from the wetland does not harm groundwater resources.
- Groundwater is the lowest carbon source of drinking water. If it is polluted by leakage from a wetland a valuable source of water may be lost for a considerable amount of time. Nitrate, heavy metals and some chemicals are sufficiently mobile in groundwater that the wetland could be a source of pollution. In general phosphorus is not mobile in groundwater and is unlikely to present a drinking water quality issue. Some pesticides break down rapidly in a wetland and if so, they are unlikely to cause an issue. However, phosphorus and pesticide pollution are site specific and should always be considered especially if rapid flow paths exist, e.g. in karstic limestone, chalk or fractured igneous bedrock areas.
- All groundwater is a potential future resource for drinking water. Groundwater nitrate vulnerable zones (NVZs) identify areas where groundwater is vulnerable to nitrate pollution and should be protected from elevated levels of nitrate leaching either directly via leakage from a wetland or via leaching from the soil during the construction process.

Key information required for outline design

- Groundwater source protection zones (SPZs), Groundwater NVZs and Groundwater vulnerability maps are all required to identify if the location is feasible and if a liner is likely to be required.
- Guidance RPS 260 and CIRIA 3736 give an indication of when a liner is likely to be required. Infiltration rates in excess of 1 X 10^{-7} m/s are likely to require a liner.
- Locations of SPZs and GW NVZs are available via the Constructed Wetland Hub.

Hydrology and drainage

Design issue to be considered, mitigated and addressed?

- The interaction of the wetland with existing surface water and shallow drainage needs to be characterised so that inputs of water to the wetland, and leakage of water from the wetland, can be identified and mitigated so that flows through the wetland can be estimated accurately.
- Historical field drainage (clay or plastic pipes) can compromise the functioning of a wetland. Therefore, information on sub-surface drainage needs to be considered either from historical drainage maps or from field investigations. The most reliable drainage maps are typically those used by the landowner themselves – however, most of these maps are very out of date and do not account for the reduction in the performance of land drains over time. A site assessment, looking for evidence of flowing land drains and trial pits to establish whether they are an issue, is often the only way to establish whether land drains or groundwater could cause an issue with the design.

Key information required for outline design

- Map of surface water flow within and adjacent to the proposed wetland location on the site. At its simplest this can be a map of the site with levels taken from LiDAR and likely flow paths drawn on, however, more detailed DEM data from a drone coupled with a SciMap flow accumulation map provides additional confidence.
- Site investigation or historical maps identifying if land drainage is present and how the impacts of this could be mitigated within the design.

Flood risk

Design issue to be considered, mitigated and addressed?

- A wetland design which could increase fluvial flood risk will not be permitted by the relevant risk management authority which is normally the Environment Agency on main rivers and Local Authorities for ordinary water courses.
- Changing a flood flow path or reducing storage capacity of the floodplain are unlikely to be permitted in flood zones 2 and 3 (main rivers) without a Flood Risk Assessment

(F.R.A). which demonstrates that flood risk has not increased. This will mean that spoil will need to be removed from the flood zone. Use the Constructed Wetland Hub to identify if this is an issue for your site.

- Wetlands which are likely to flood will be at risk of having reduced or unpredictable treatment efficacy at times when they are inundated. They may also require more frequent maintenance. This is a serious issue for treatment wetlands which need to have certainty over the reductions they will achieve (e.g. nutrient mitigation wetlands or those with permit limits). If the client and regulator can accept lower nutrient removal during high flows, when dilution is likely to be significant, then locating wetlands in flood zones 2 and 3 may not be an issue.
- Surface water flooding is also an issue. It is unlikely that a wetland could increase surface water flood risk, but it is important to consider this risk and whether the wetland is in an area which suffers from surface water flooding. Use the SW flood maps in the Constructed Wetland Hub to identify if the site is prone to surface water flooding.

Key information required for outline design

- A map to show if the wetland is in a flood zone. If the wetland is in Flood zone 2 or 3 (fluvial flooding) it is highly likely that it will require a flood risk assessment including a plan for the removal of spoil.
- A map to show if the wetland is in a surface water flood risk area. If it is in an area of surface water flood risk, provide a mitigation strategy.
- An evaluation of the impact of fluvial and surface water flooding on the functioning of the wetland.

Protected sites and species

Design issue to be considered, mitigated and addressed?

- If the location is in, or near, a protected site, and could impact the conservation objectives of the site, a permit will be required from Natural England. The Wetland Hub can be used to identify national protected sites but not Local Wildlife sites. The location of these is available from the Local Authority or the local Biological Record Centre and will also be identified in an EIA for the site if it is available.
- If protected species are present at or near the site and could be impacted by the project, a consent will be required from Natural England. Information is available from the local Biological Record Centre or an EIA if one is available for the site.
- What is the ‘ideal’ habitat at the location? Natural England currently publish Habitat Network Opportunity maps and priority habitat maps. These enable the designer to see what the ‘ideal’ habitat would be and if a wetland will complement or conflict with this usage. These maps will be progressively replaced by the Local Nature Recovery Strategies (LNRS).

Key information required for outline design

- Map of international and national protected sites for nature conservation (SAC, SPA, SSSI, Ramsar sites and MCZs).
- Map of locally protected sites (Local nature reserves, Local wildlife sites and local geological sites).
- Map of other protected areas (National Parks, AONBs and Heritage Coast).
- List of protected species (presence near the site location).
- Map of Habitat Network Opportunities and Priority habitats including priority river restoration sites. Ultimately the LNRS will be required.
- In some locations, a full EIA may be available if it has been done for a nearby site, e.g. a STW.

Land use

Design issue to be considered, mitigated and addressed?

- It is important to understand the current and historical land use of the site because this could indicate historic industrial contamination or nutrient enrichment. Construction of a wetland could mobilise this historic pollution and impact receiving waters.
- If the land is currently under an agri-environment scheme, payments may be lost if the scheme is delivered.

Key information required for outline design

- Map of current land use and commentary on any previous land use that might cause an elevated risk of pollution from the wetland either during construction or operation. Although the latest land use map is available on the Constructed Wetland Hub, additional information from the landowner to identify if a high-risk land use has occurred in the past e.g. outdoor pigs or poultry will add real value.
- Maps of known contaminated sites. This may be available from the local authority.
- Map of active agri-environment schemes.

Ownership

Design issue to be considered, mitigated and addressed?

- A project can only be delivered with the agreement of the landowner. There is limited information on landownership available online. There is no real alternative to visiting the site and making contact with local landowners who are likely to know who owns the site of interest. Using staff from local third sector organisations is a pragmatic way of using local networks and introducing the potential wider benefits of the scheme rather than just focusing on the potential disbenefits and negotiating to get the best land value.

Key information required for outline design

- Details of the landowner and, if possible, their attitude towards the potential development. This is a potential blocker for the whole project and needs to be established before detailed design is progressed.

Archaeology and heritage

Design issue to be considered, mitigated and addressed?

- Archaeological remains and landscape features may need to be protected so that they are not lost. The best way to minimise the risk that archaeological remains will delay construction and increase costs is to identify the issue early on and plan for it.
- Scheduled monuments have additional protection and should not be impacted by development.
- Peat soils will also preserve environmental records in situ and should be protected.
- Archaeological or heritage value risk assessment based on advice from the Local Authority archaeologist and any site investigation that has been conducted. It is often possible to identify an elevated risk of archaeological issues from local history societies or key landscape feature such as ridge and furrow features or ancient greenways and roman roads.
- The heritage value of the site and its landscape can be important. The feasibility of the wetland design needs to consider how to accommodate landscape and heritage issues.

Key information required for outline design

- Local knowledge from the site visit or Local Authority archaeologist.
- Map of scheduled monuments.
- An archaeological risk assessment may be available if the location is near an existing site e.g. STW.

Rights of way and public access

Design issue to be considered, mitigated and addressed?

- Public rights of way cannot be closed or diverted, even temporarily, without permission from the local authority.
- Public access to the completed wetland will improve its amenity value, however, it may also increase H&S or vandalism concerns.
- Conversely, public access provides an opportunity to integrate the wetland design with wider communication and public awareness raising opportunities. Such opportunities can add value to the overall wetland scheme.

Key information required for outline design

- Map of the nearest public rights of way to the site.

Birdstrike risk

Design issue to be considered, mitigated and addressed?

- Wetlands can attract birds which maybe an issue if the site is near an airfield. This is especially an issue for large wetland birds such as geese and swans and also large flocks of birds such as starlings.
- The risk of birdstrike will depend on the type of airport and its associated usage by planes. An evaluation of risk needs to be within the context of the type of airport.
- Airports may have their own birdstrike risk management programmes or plans. These should be consulted and any mitigation of birdstrike risk should be derived through consultation and the development of a mutually agreed strategy.

Key information required for outline design

- Map showing the nearest airfields and the type of airfield (commercial, military etc) along with any proposed mitigation strategy
- Link Airfield Finder

Historic landfill, coal mining and contaminated ground

Design issue to be considered, mitigated and addressed?

- Historic contamination from landfills or industry can be remobilised and released into the environment if there are excavation works. This could cause increased pollution.
- Areas with historic coal mining pose a potential risk to a new wetland of subsidence.
- Depending on the buried materials, historic landfill may pose a threat to the efficacy of the project. For instance, the potential removal of large volumes of buried asbestos may contribute significantly to the overall project costs.

Key information required for outline design

- Map of historic landfills and contaminated land.
- A site investigation report may be available for wetlands near to existing sewage treatment works or other significant engineering works.

Unexploded ordinance

Design issue to be considered, mitigated and addressed?

- Uncovering unexploded ordinance will delay project construction and increase costs.

Key information required for outline design (Optional)

- Identify presence or absence of unexploded ordinance Link Risk Maps | Zetica UXO

Services and infrastructure

Design issue to be considered, mitigated and addressed?

- Buried and overhead services (telecon, electricity, gas and water) could all be impacted by the creation of a wetland. Moving services is expensive and time consuming and requires the involvement/approval of the service provider.
- It is often easier to design around known services so that they are not impacted.

Key information required for outline design

- A full-service search along with maps of any services identified. The locations should be plotted on the maps of the potential wetland sites to show their relative position. Also consider services that could be affected by access to the site. Buried services often require protection from heavy construction traffic and this needs to be agreed with the service provider. Overhead services also require protection to ensure that they are not impacted by cranes or other construction plant.
- There are number of online platforms which can be used to locate services however, none of these platforms identifies all the services that could occur within the site of interest. It is particularly important to approach the local water company and British Telecom separately as their services are often not covered. Key risks from services include:
    - High voltage electricity
    - High pressure gas
    - Fibre optics cabling for telecons
    - Pressurised clean water mains
- Links for some platforms:
    - National Underground Asset Register. This is the gold standard but your organisation needs to register before it can use it.
    - Home - LinesearchbeforeUdig (lsbud.co.uk)
- A site investigation report for a nearby location e.g. STW or construction site is likely to already have this information.
- All information on services should be incorporated into the Design Stage Risk Assessment.

Proximity to housing

Design issue to be considered, mitigated and addressed?

- Where wetlands are close to housing, the opportunity for maximising the benefit of the wetland as an amenity should be particularly closely considered.
- If wetlands are treating odorous effluents, smell can be an issue, however, it is important to compare the potential odour issue from a wetland with the engineered alternative.

- Open water and human health issues associated with sewage are a potential health and safety risk, however, it is important to compare this with the engineered alternative and the fact that wetlands occur naturally within the environment.

Key information required for outline design (Optional)

- Map showing location and distance to nearest housing.
- Assessment of the potential for amenity use.
- Mitigation strategy for health and safety and odour as this will have impacts for the design and costs.

Nature recovery and LNRS

Design issue to be considered, mitigated and addressed?

- Wetlands have the potential to be a very important part of a habitat network which will allow catchment and nature recovery. However, there are locations where wetlands would not be appropriate as they could displace a more valuable habitat type.

Key information required for outline design

- Map of the habitat opportunity network identifying that the location is suitable for a wetland. In time the Local Nature Recovery Strategy (LNRS) should be used to minimise the risk that a constructed wetland habitat will compromise the local habitat network. Constructed Wetland Hub
- **Optional.** Identification of potential biodiversity net gain credits using The Defra statutory Biodiversity Metric tool. This could provide a significant additional source of funding to optimise the habitat benefit of the wetland.

Decommissioning

What is the issue to be addressed?

- As part of the Construction Design and Management (CDM) regulations 2015 a decommissioning plan should be included in the design stage risk assessment.

Key information required (Required for wider feasibility of project)

- Be clear about the design life of the wetland, and what will happen to the site after decommissioning.
- Consider the fate of the nutrient captured in the wetland during the decommissioning process.
- Consider the fate of other captured pollutants if appropriate, for instance heavy metals and microplastics.

Regulatory considerations

What is the issue to be addressed?

- Environmental permits are likely to be required for many constructed wetland projects, especially near Main Rivers. Early dialogue with the Environment Agency and Natural England is recommended to identify potential permitting requirements. These are likely to vary from project to project.

Key information required (Required for wider feasibility of project)

- A list of the permits that the Wetland designer considers will be required along with an assessment of the likelihood that they will be granted.
- **Optional.** A narrative on each permit identifying any engagement with the relevant regulator and advice already received.

Constraints, feasibility outcome and options assessment

All of the above considerations need to be evaluated to assess whether it is feasible to create a treatment wetland that will satisfy the design objectives.

What is the issue to be addressed?

- A summary table which describes the constraints identified for each site and any further information needs and gaps. This provides a sound audit trail to justify the option that is recommended.
- Ideally, the constraints should also be offset by a summary description of the potential benefits that the preferred scheme can provide.

Key information required

- **Optional.** A summary table of options and constraints.
- **Optional.** A narrative justifying the preferred option and highlighting why it is better than other locations.

Data availability summary

Table 3.1 Summary of data sources

Data group	Supporting data	Data availability
Topography and levels	Lidar	Constructed Wetland Hub

Soils	Soilscapes	Constructed Wetland Hub
	National Soil Map	Cranfield University via their Mapshop,
	Soils report	Landis Soils Site Reporter service
	Peaty soils locations	Constructed Wetland Hub
	Infiltration test	Infiltration systems: groundwater risk assessments - GOV.UK (www.gov.uk)
Geology and hydrogeology	BGS 50k Geology layers	Constructed Wetland Hub
	Groundwater flooding	Paid-for data available from JBA and BGS
Groundwater protection	Source protection zones (SPZs)	Constructed Wetland Hub
	Groundwater NVZs	Constructed Wetland Hub
	Groundwater vulnerability	Available for non-commercial purposes on request via data.gov or for commercial purposes via BGS.
Hydrology and drainage	Historical maps	Historical Ordnance survey maps for England and Wales (1842-1952) available from the National Library of Scotland
	Lidar	Constructed Wetland Hub

	Property maps showing land drainage	-
	Rainfall	Constructed Wetland Hub
Flood risk	Surface water flooding	Constructed Wetland Hub
	Fluvial flooding	Constructed Wetland Hub
	Environment Agency flood alert areas	Constructed Wetland Hub
Protected sites and species	Priority habitat inventory	Constructed Wetland Hub
	Habitat networks	Constructed Wetland Hub
	Designated sites (SAC, SPA, SSSI, Ramsar sites and MCZs)	Constructed Wetland Hub
	Protected areas (National Parks, AONBs and Heritage Coast)	Constructed Wetland Hub
	Protected species	Local Environmental Record Centre
Land use	Land cover map from CEH	Constructed Wetland Hub
	Agri-environment schemes	Constructed Wetland Hub
	Landfill sites	Constructed Wetland Hub
Ownership	Local knowledge	-
	Title register	Purchase the title register for land or property via Gov.uk

Archaeology and heritage	Historic England Heritage at Risk Register & the National heritage list of England	Constructed Wetland Hub
Rights of way and public access	Public rights of way	Constructed Wetland Hub
Birdstrike risk	Airfields	Airfields of Britain Conservation Trust – Airfield finder
Historic landfill, coal mining and contaminated ground	Landfill sites	Constructed Wetland Hub
	Contaminated land	Contact local authority
	Inventory of Closed Mining Waste Facilities	Constructed Wetland Hub
Unexploded ordinance	Risk maps	Zeticauxo
Services and infrastructure	Key risks from services include: High voltage electricity High pressure gas Fibre optics cabling for telecons Pressurised clean water mains	National Underground Asset Register – requires registration. LinesearchbeforeUdig Open Infrastructure Map
Proximity to housing	Ordnance Survey maps – building footprints	Constructed Wetland Hub
Nature recovery and LNRS	Habitat Network layers – enhancement zones	Constructed Wetland Hub

Revisiting wetland sizing

Following the constraints and options assessment, it is good practice to revisit the sizing calculations to assess whether there are any issues which compromise the original area required for the treatment or whether the amount of nutrient to be removed will change due to the site conditions. The sizing calculations should follow the approaches described above.

Outline design process

Once feasibility issues have been assessed and the sizing of the wetland has been confirmed, it is recommended that an outline design is produced to scope out the layout of the wetland. This doesn't necessarily need to be a detailed drawing with a high degree of accuracy, however computer-aided design (CAD) software is generally used to produce drawings. The outline design needs to consider the following elements:

- The overall configuration and number of different wetland cells (assuming a multi-celled wetland design is being considered).
- The location of the inflow to the wetland and the outflow back to the receiving environment.
- Any constraints or areas that need to be avoided.
- The overall flow pathway through the wetland treatment system.
- The location of water management and control features.
- Approximate levels (in metres above Ordnance Datum) of individual wetland cells. To include formation base level, media level, operating water level, overflow level, bund levels and the inlet and outlet levels.

For some wetland projects, a robust outline design may be sufficient to guide construction, However, this can depend on the complexity of the design, the construction methods required and the competence of the people or organisation implementing the wetland.

Spoil considerations

As part of the outline design process, consideration also needs to be given to the amount and type of spoil that might be generated from the construction of the wetland or whether material may need to be imported. This needs to approximate the volume to be removed and also the location for disposal. The spoil arising might have value. For instance, it might be possible to sell the topsoil. Similarly, the spoil can be used, if the topsoil is buried and the soil profile inverted, to create low-nutrient substrate for habitat creation, such as wildflower meadows. Ideally, to keep costs down and to optimise sustainability, spoil should be disposed as close to the wetland site as practicable. An indication of the spoil disposal area should also be incorporated into the outline design if appropriate.

Water balance

Based on the parameters defined in the outline design, it is necessary to assess whether there is sufficient water to allow the wetland to function in summer during possible hot, drought conditions and during periods of excessive rainfall or storm inflows. For FWS treatment wetlands, and particularly those designed to remove Phosphorus, it is essential that they do not undergo periods of drying out. Therefore, calculating an annual and seasonal water balance is critical. The water balance needs to consider the inflows to the wetland, the change in storage capacity within the wetland over time and the outflows from the wetland. The influence of climate change on the water balance should also be factored in. The following elements should be combined to assess the wetland water balance and to identify whether the size of the wetland does not mean that it will dry out.

- Have all inflows been characterised, including precipitation surface inflows, pumped or supplied inflows or ingress from groundwater (unlined constructed wetlands only)? Have all possible outflows been characterised, including evapotranspiration, infiltration and controlled discharges?
- Has the change in storage (the water balance) demonstrated on a monthly basis that there will not be a water deficit?
- If there is a potential deficit, is it possible to manage this through storage of excess water within the wetland itself without compromising the wetland functioning?
- Has the impact of climate change on the water balance parameters been considered?

It might be necessary to revisit the outline design and make modifications to ensure that there is not a deficit in the water balance, or that any potential deficit can be managed through hydrological manipulation within the wetland system.

Hydrological control and management

As part of the outline design, consideration needs to be given to how water will be delivered to the wetland, how water will be managed in the wetland and how will it return to the receiving environment. The following issues need to be considered in the outline design process:

- The ability to move water under gravity and avoid pumping infrastructure.
- The type, location and number of water control structures.
- Pipe lengths, diameter and gradients in order to prevent sedimentation and maintain conveyance.
- Water balance implications on the hydrological management.

Sediment load

Almost all sources of water treated by wetlands will have a sediment load. Whilst a regular input of sediments can be beneficial in replenishing potential Phosphorus adsorption sites, too much sediment accumulating in the wetland can compromise the long-term functioning and nutrient removal capacity and could potentially result in the wetland becoming a net source. From a management perspective, it is also important to estimate the sediment accumulation rates to inform possible desilting and desludging activities. The following needs to be considered at the outline design stage:

- Characterise the sediment load entering the wetland.
- Convert the sediment load into a volume.
- Assess the rate that this volume of sediment will accumulate across the wetland area.

It may be necessary to revisit the outline design and include a sacrificial sediment trap or settlement pond to remove sediments which might compromise the long-term functioning of the wetland system. Alternatively, the outline design might need to include a dedicated area that is managed for sediment removal on a routine basis.

Designing for multiple benefits

The multiple benefits that have been incorporated in the wetland development need to be incorporated into the outline design. This is particularly important if physical or even visual access is required. The consideration of multiple benefits should not be an afterthought but should be included at the outline design stage.

Designing for sustainability

The outline design stage is the appropriate time to establish sustainability criteria, such as moving water under gravity, reworking in situ soils, or minimising the number and type of heavily engineered water control structures.

Planning and permitting

This section is based upon professional experience of delivery of wetland projects and does not constitute official ‘statutory’ guidance.

The vast majority of nutrient mitigation wetlands will require planning permission and at least one type of permit or licence. It is important for the designer to understand what the requirements are, or are likely to be, as early as possible in the project timeline. This is because:

- The planning process may take considerable time, with statutory timeframes for the validation of applications and feedback from statutory consultees and the public before a decision is made.
- Feedback from statutory consultees* and other stakeholders during the planning process can often require elements of the design to be altered in order to overcome objections, especially if the applicant had not considered potential requirements from the start. This can cause significant delay and re-work.
- Ignorance is no defence – it is incumbent on the designer to understand which permits will be required for the proposed wetland to be constructed and operated. Don’t leave it too late to find out.

*The full list of statutory consultees is as follows:

Canal and River Trust
Civil Aviation Authority
Coal Authority
Crown Estate Commissioners
Department for Culture, Media and Sport
Department of Energy and Climate Change
Department for Environment, Food and Rural Affairs
Department for Transport
Environment Agency
English Heritage
Forestry Commission
Garden History Society
Health and Safety Executive
Highways Agency
Ministry of Defence
Natural England
National Air Control Transport Services and Operators of Officially Safeguarded Civil Aerodromes
Rail Network Operators
Sport England
Theatres Trust
Toll Road Concessionaries

Planning Bodies (including Local Planning Authorities, and Local Highway Authorities)
Please note not all statutory consultees are consulted on all planning applications. Further information can be found here:

https://www.gov.uk/guidance/consultation-and-pre-decision-matters

Key considerations for planning and permitting

It is highly recommended that a qualified planning consultant is included in the project delivery team, especially one that is experienced in environmental projects. They will liaise with the LPA and coordinate the application, ensuring that the process runs efficiently.

There are two approaches to the planning process:

1. Outline Application – Reserved Matters Application
2. Pre-application – Full Application

The approach taken will ultimately depend on the clients' attitude towards risk. The first approach is more risk averse, as a decision in principle can be obtained without having to commit to so much design and survey work. Reserved matters are typically addressed by the detailed design, which can be instructed with the comfort that outline planning permission is already secured.

The second approach commences with a pre-application, which only provides advice from the LPA, not a decision. A lot more preparation is required to submit a full planning application, meaning that the client is exposed to more commercial risk before a decision is obtained. However, it can be a quicker process overall.

There is a tendency for some clients to seek the fastest possible outcome for the lowest capital outlay, which is certainly understandable. This is where the second approach is taken (full application), but only outline design is submitted, not the detailed design. This can be a false economy, because even if full planning is granted, there may be necessary changes to the design at the detailed design stage that constitute 'material amendments' in the opinion of the LPA. In the worst case, if the material amendments cannot be avoided, then a revised planning application will be required – adding more cost and delay. Outline planning permission provides much more flexibility, meaning that changes can be made at the detailed design stage.

Regarding permits, it's important to note that different permit applications require differing levels of detail. For example, an abstraction permit will require details of the location of the abstraction, the daily flow (m^3/d) and the peak flow (l/s) including any seasonal variations throughout the year, which can be determined relatively early in the project. However, a flood risk activity permit application will require not only detailed design, but also

construction method statements from the contractor. This is information that will only be available much later in the project.

Flow diagram – narrative

The following flow chart is based upon professional experience of delivery of wetland projects and does not replace official permitting guidance for nutrient mitigation wetlands, which can be found here https://www.gov.uk/guidance/nutrient-mitigation-check-if-you-need-environmental-permissions

It should be noted that the flow chart is specific to England and not necessarily reflective of ALL the requirements of the planning and permitting process, it is just an example of the most likely issues your wetland project might need to consider. Every project is unique, with site specific issues that may only be picked up by statutory consultees to the local planning authority (LPA), such as the Environment Agency (EA), Natural England (NE), Water & Sewerage companies (WaSCs) etc.

It should also be noted that the second stage of the flow chart does not cover the following applications, which may well constitute viable nutrient mitigation projects:

- Wetlands fed from package treatment plants (PTP's)

Private PTP's are regulated under the Environmental Permitting Regulations, specifically the 'General Binding Rules' which came into effect in January 2015. They are also regulated under Building Regulations (Doc H). In order for any wetland to be considered viable as a nutrient neutrality scheme, it must be delivering 'over and above' the minimum requirements of the regulations. Further details of the general binding rules and Building Regulations can be found here:

https://www.gov.uk/permits-you-need-for-septic-tanks/you-have-a-septic-tank-or-small-sewage-treatment-plant

https://www.gov.uk/government/publications/drainage-and-waste-disposal-approved-document-h

- Wetlands fed by groundwater (for nitrogen mitigation only)

Wetlands that are fed by groundwater (i.e. springs) may need an abstraction / impoundment license from the EA. It is always advisable to check with the agency. Further advice can be found here:

https://www.gov.uk/guidance/check-if-you-need-a-licence-to-abstract-water

All other sections of the flow chart (1 and 3-9) can be used for wetlands in the above applications.

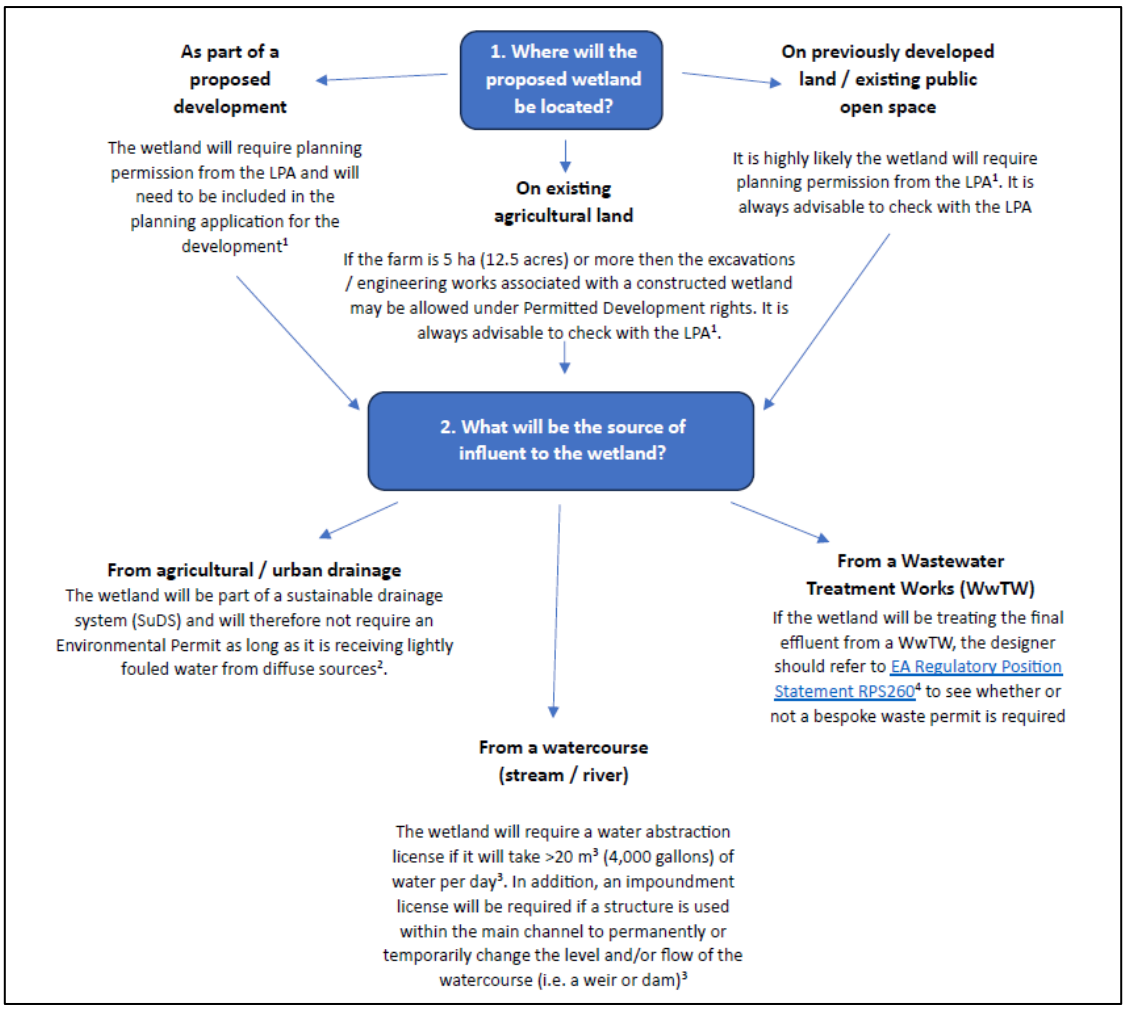


Figure 4.1a. Planning Flow diagram. Location and source of influent

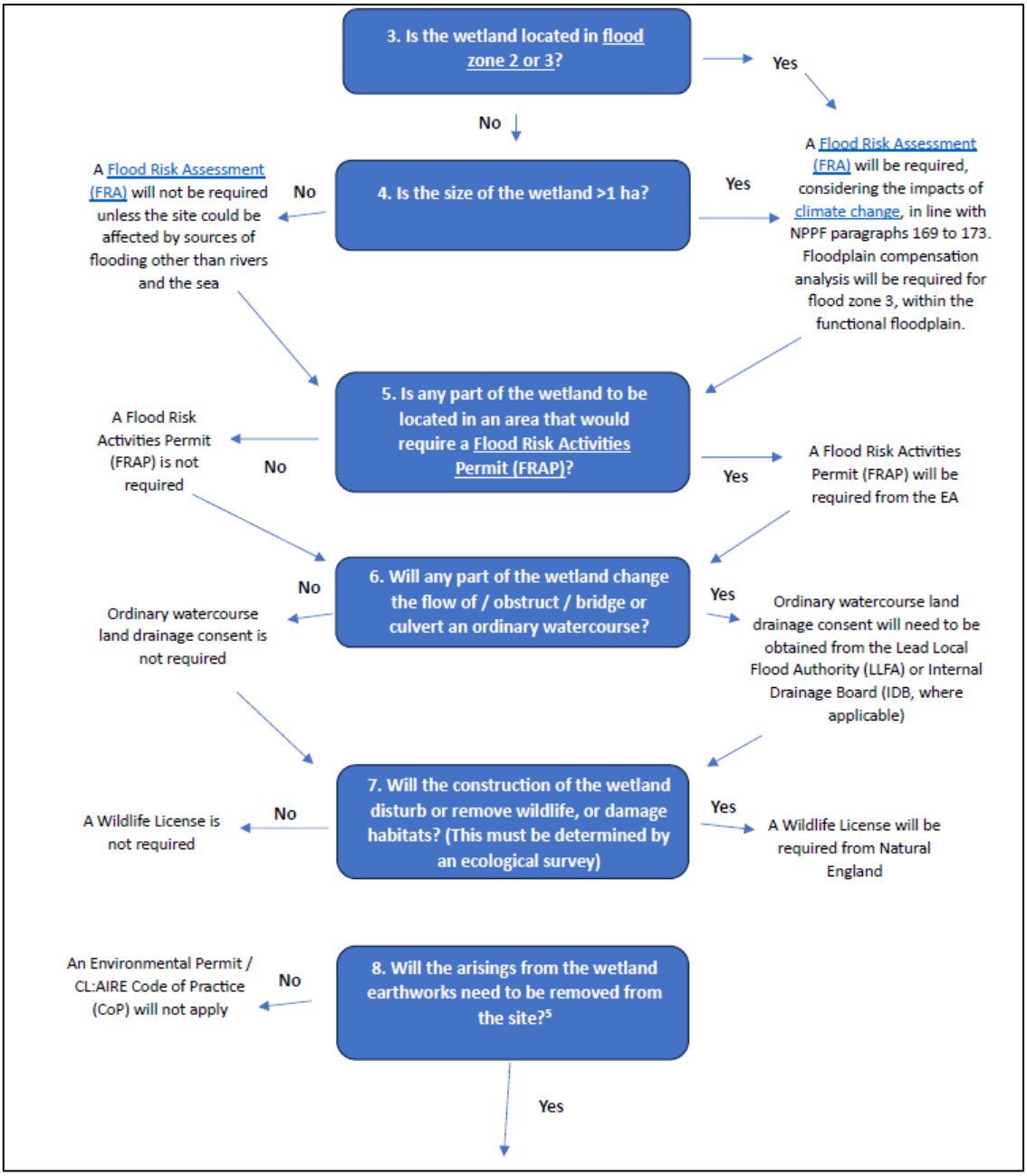


Figure 4.1b. Planning Flow diagram. Flood risk, wildlife and waste considerations

Figure 4.1c. Planning Flow diagram. Further waste and wildlife considerations.

Advice notes

1. Where planning permission is required, it is strongly recommended that both planning permission and all applicable permits are applied for simultaneously (a process known as 'twin tracking'). It should be noted that both the Environment Agency (EA) and Natural England (NE) are statutory consultees to the Local Planning Authority (LPA) and as such they may be consulted as part of the planning process. This will be at the discretion of the LPA. Where the statutory consultees are consulted, they may issue written advice on permit / licence requirements. Applicants will need to ensure that they understand what permissions are required and twin track them.
2. For agricultural drainage, diffuse pollution sources include runoff from fields and yards and tracks where livestock / materials are in transit but not stored for any period of time. Slurry and silage effluent are point sources and have a very high concentration of nutrients and other pollutants. It is not recommended to use constructed wetlands to treat slurry and silage effluent. Other point sources such as abattoir effluent, dairy parlour wastewater or heavily contaminated yard washings can be treated by constructed wetlands, but these would not constitute SuDS and an Environmental Permit will be required for these applications.
3. A 'transfer abstraction licence' is likely to be the licence type needed for most nutrient mitigation wetlands, authorising abstraction from an existing watercourse to transfer water into the wetland (e.g. into the channels that form the managed wetland system) in cases where the wetland has an outflow back to a water body. In some cases, a full abstraction licence may be appropriate if the wetland is not returning any water. It is not expected that a temporary licence will be needed in any cases, as any abstraction into wetlands will be for longer than 28 consecutive days. Applicants should always be aware of the timeframe for pre-application advice, and/or for the processing of the actual permit application which can be many months. Further guidance can be found here: https://www.gov.uk/guidance/water-management-apply-for-a-water-abstraction-or-impoundment-licence
4. The regulatory position statement (RPS) 'Using wetlands to improve treated effluent discharge: RPS 260' sets out the Environment Agency's enforcement position for the

waste operation of nutrient mitigation wetlands, operated by parties other than WaSCs. The RPS is applicable for surface flow nutrient treatment wetlands with submerged and emergent vegetation where all the following apply:

- they provide further treatment to treated final effluent that has been discharged directly into the nutrient treatment wetland from a WaSC wastewater treatment works;
- the discharge from the wastewater treatment works is authorised by an environmental permit;
- the nutrient treatment wetland is not operated by, or on behalf of, a WaSC. If the wetland is to be owned / operated by the owner of the WwTW (i.e. the statutory sewerage undertaker) then a variation of the existing Environmental Permit will be required. For non-sewerage WwTW applications (i.e. wastewater treatment plants treating industrial effluent and discharging to the environment), a variation of the existing Environmental Permit will be required.

5. The most sustainable approach is to balance the cut and fill earthwork requirements, so that there is no need to import or export soil. In addition, the quality of the soil on site must be assessed from a ground investigation which should take samples of topsoil and subsoil for laboratory analysis against waste acceptance criteria (WAC). If the site is brownfield, additional assessment using the Contaminated Land Exposure Assessment (CLEA) and/or Category 4 Screening Levels (C4SLs) should be undertaken to inform a quantitative risk assessment.
6. This is the least sustainable and most expensive option. Spreading the soil on other non-agricultural land may be possible with the landowners permission and subject to the use of the CL:AIRE CoP. If it is not possible to adhere to the CoP then an Environmental Permit for waste to land deployment or waste recovery will be required.
7. This is not to be confused with the HRA for any new residential developments whose water pollution (nutrient) impacts are to be mitigated by the wetland. This relates purely to the wetland development only. Whilst the wetland may be mitigating the impact of other developments, the impact of the construction, operation and maintenance of the wetland development itself must be properly assessed.

Detailed design

Detailed design is critical to the success of any wetland project, as it provides the information required to construct, operate and maintain it.

Project Information Checklist

Before starting the detailed design, it is important to ensure that all pertinent information relating to the site and the design objectives is available from the feasibility and outline design process. The following checklist includes the critical information that should already be available from the outline design, plus additional information which may not yet have been obtained.

- Have all incoming flows been identified and characterised (to provide (at least) a total average flow in m3/d, plus the peak design flow in l/s, realistic duration of drought periods)?
- Has modelling been undertaken to provide a target area of active treatment wetland (net of berms and hydraulic control structures)?
- Is the site boundary clearly defined, and access point(s) identified (both for construction, and ongoing operation and maintenance)?
- Has a topographical survey been carried out, providing details of site levels, any existing tracks, ditches, vegetation, manholes, existing hardstanding etc?
- Do you have a conceptual ground model based upon intrusive ground investigation with details of the soil characteristics, including permeability, depth to groundwater and bedrock and laboratory analysis for any contaminants (i.e. waste acceptance criteria)?
- Have details of all known utilities within the site boundary been provided? (gas, electricity, water, sewerage, telecoms).
- Have details of any protected trees (including root protection zones) and/or other habitat/species been provided following an ecological survey?
- Have any public rights of way (PROW) plus any rights of access and egress by neighbouring landowners been clearly identified?
- Do you understand the constraints posed by archaeological interest at the site?

Consideration of constraints

In order to ensure that all constraints are considered in the detailed design, they may all be plotted on one site layout drawing. It is often convenient to use topographical survey as the basis for the drawing, with utilities, root protection zones and any protected habitat areas superimposed.

Additional constraints may be posed by topography, proximity to watercourses and areas of flood risk.

Electricity Pylons & Overhead Cables

It is advisable to avoid significant construction work in areas beneath overhead cables and around pylons / stays, as minimum clearances must be maintained at all times. This applies to both the construction and the ongoing management and maintenance of the wetland. Further advice can be found in the UK Health and Safety Executive's (HSE) Guidance Note GS6 "Avoiding danger from overhead Power lines" and is summarised here: https://www.hse.gov.uk/electricity/information/overhead.htm

Additional consideration must be given to the need for maintenance access to pylons and overhead cables by the Distribution Network Operator (DNO). Routes of access from the nearest road must not be cut off by the wetland.

Buried Services

Buried services will typically include water mains, sewers, gas mains and cables of various voltages. They should not be covered by the wetland cells and a typical horizontal clearance of at least 2.0 m should be maintained between buried services and the nearest point of wetland construction. Further advice can be found in the HSE guidance note HSG47 "Avoiding Danger from Underground Services" here: https://www.hse.gov.uk/pubns/books/hsg47.htm

If necessary, it is possible to cross buried services with pipes or channels, as with any other construction project. This can be a useful way of linking wetland cells to optimise the available area. Minimum vertical clearances must be maintained between the services and the pipe or channel.

Detailed design drawings showing the location of buried services should always be clearly labelled 'exact depth and location of buried services to be confirmed by trial holes, in accordance with safe working practices.

Existing Trees & Root Protection Zones

Where existing trees and hedgerows are to be retained within the site boundary, the preservation of root protection zones should be considered to ensure the ongoing health of the tree. This includes the use of heavy plant and machinery tracking over the area, which could cause erosion of the soil and exposure of roots, and/or compaction of the soil at depth, preventing the passage of air and water through the pore spaces. Further guidance on best practise can be found in BS 5837:2012 'trees in relation to design, demolition and construction.

Proximity to Main Rivers & Ordinary Watercourses

Natural rivers are dynamic ecosystems which will move about as the river water interacts with the soils in the river banks and river bed and the land in its floodplain. Floodplains are natural places for wetlands to occur and if a wetland is to be constructed in a floodplain it should be designed to complement the existing dynamic river / floodplain system. It is particularly important to avoid hard engineering around the river banks wherever possible and to avoid raising levels in the floodplains unduly as these activities will impair the natural function of the river and will be at risk of damage during flood events. Good design will require careful thought as to how the river, its floodplain and new wetland will interact as a whole, and may warrant specialist input from a geomorphologist. The following rules of thumb may assist in guiding the design process.

- For areas adjacent to main rivers, it is advisable to maintain a clearance of at least 10m from the nearest point of the wetland construction to the top of the riverbank. This is to maintain an adequate riparian buffer zone.
- For intake or outfall headwalls within the riverbank of main rivers, the design will need to consider the risk of erosion of newly placed backfill soil around the headwall by the river. Some kind of scour protection will normally be needed.
- For ordinary watercourses and ditches, it is advisable to maintain a clearance of at least 4m from the nearest point of the wetland construction to the top of the bank. However, you must check with the Local Lead Flood Authority (LLFA) or the Internal Drainage Board (IDB) (if applicable) in case it is a managed watercourse. If so, additional clearance (often 8m) may be required for ongoing maintenance activities.
- Precautions will normally be needed to avoid causing undue siltation or other pollution in the river during construction.

Flood Risk Areas

Any existing areas of flood risk will have been identified at the feasibility stage, and if needed a flood risk assessment (FRA) should have been completed in parallel with the outline design.

The FRA may stipulate specific constraints or measures that need to be incorporated into the detailed design, such as:

- Maximum height of berms within the functional floodplain (flood zone 3) to prevent obstruction to the passage of certain flood events.
- No net loss of available flood storage volume (this may apply to surface water flood risk areas as well as flood zones 2 or 3 and will be assessed on a level for level basis within the functional floodplain).

Topography

Where sites are sloped, the earthworks will necessitate a combination of cutting and filling to create FWS wetlands. Consideration of the slope used for cuttings and embankments will be very important as it will influence the available area for the wetland cells. Slopes of 1V: 3H or shallower are typically recommended as they offer more stability, although steeper slopes are possible subject to geotechnical design.

There is a trade-off between slope angle and available wetland area, whereby steeper slopes afford greater wetland areas but at the cost of more complex geotechnical design or materials. Proprietary geocellular confinement systems or retaining walls can be used to allow steeper slopes to be constructed, some of these can offer a natural vegetated finish, however they add to the cost and embodied energy and carbon of the wetland.

Additional considerations when working on sloped sites are the inclusion of accessways to get from one level to another. They should not be prohibitively steep for maintenance vehicles / equipment. Very steep slopes should be designed out of the wetland wherever possible. Where this is not possible, edge protection such as fencing may be needed to prevent falling from height.

There should also be provision of suitable land drainage within the earthworks to prevent the buildup of porewater pressure which can cause instability and slip failure.

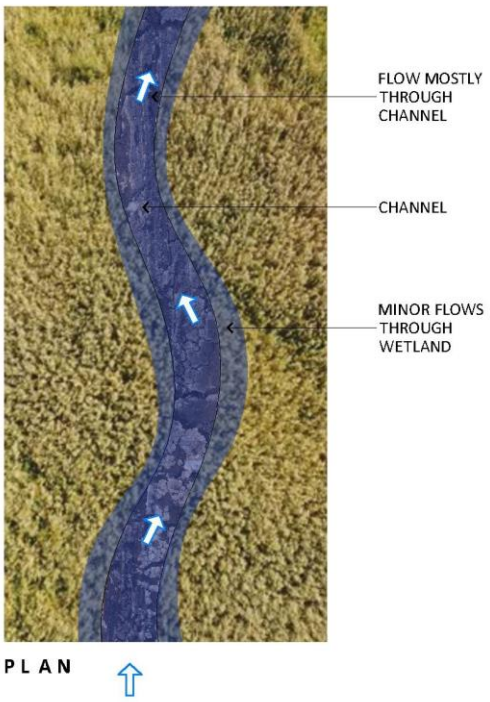
Hydraulic performance

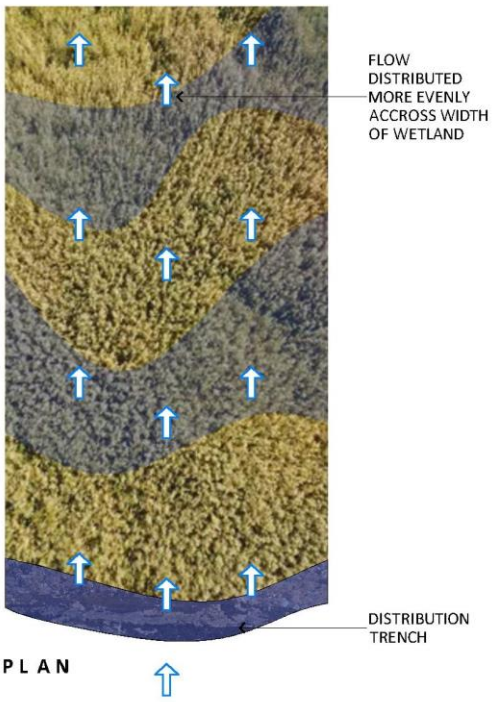
In nature, when water flows over soil there is a tendency for soil to erode in areas where the water velocity is highest. This erosion creates channels in the soil, reducing the level, and causing a greater volume of water to flow through the channel, further increasing erosion. This is the natural process by which rivers and streams form.

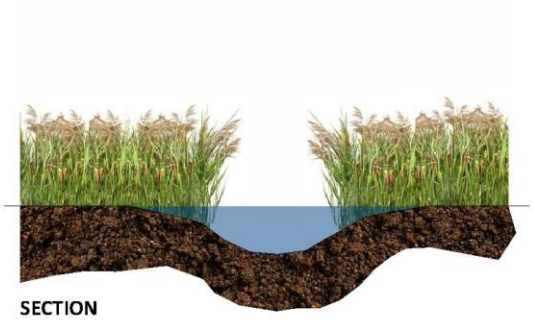
In areas away from the central channels of rivers and streams and in areas of the landscape where hydraulic gradients are commonly low, water moves slowly, and sediments carried by the water are deposited. It is in these areas that densely vegetated wetlands can form, and the microbiological and plant communities have sufficient time to readily process the dissolved and particulate forms of nutrient. In natural systems (such as riparian wetlands) most of the water will flow more rapidly in channels with low vegetation density. Only a small proportion of river water will enter riparian wetland areas.

Designers of treatment wetlands are trying to recreate the heavily vegetated areas of slow-moving water where efficient nutrient processing can occur and applying a larger amount of water through these systems by controlling the flow paths, thus improving the treatment that would be offered by a truly natural system.

FIGURE 5.1 – RIPARIAN VS TREATMENT WETLAND FLOW PATHS







RIPARIAN WETLAND FLOW PATH

IDEALIZED TREATMENT WETLAND FLOW PATH

To maximise the treatment efficiency of a Free-Water Surface wetland, considerable effort should be devoted by the designer to maximising the area of the wetlands that will receive a continuous throughput of water and minimising opportunity for preferential flow paths to form, while recognising that areas of the wetlands with very slow moving water appear to be beneficial for many ecological and treatment functions.

The principal aims of hydraulic design of a treatment wetland will therefore be:

1) to encourage water to disperse in the wetland. This will maximise the area of the wetland that is available to treat the water.

2) to create a wetland in which the water can move slowly.

These two aims can often be at odds with one another, and a compromise must be sought. Furthermore, it is important to keep in mind that perfect hydraulic efficiency will never be attained, and it is important that a designer's efforts to achieve this do not unduly undermine other design aims of the wetlands (for instance having a large treatment area, a diverse wetland habitat complementary to surrounding ecosystems, or a pleasing fit with the surrounding landscape). This is discussed further in the paragraphs titled “Designing wetlands to optimise hydraulic efficiency”.

Flow Rate, Hydraulic Loading Rate, Hydraulic Retention Time and Velocity

It is important for a wetland designer to have a good understanding of these concepts when considering the hydraulic performance of a wetland so some discussion here is considered worthwhile.

The *flow rate* (often denoted Q in wetland models) is the total volume of water entering (or leaving) the wetland in a fixed period of time. It is often described in units of cubic metres per day when describing the hydraulic load that reached the wetland, though it will be often measured in litres per second or litres per minute if measured instantaneously (eg over a triangular inlet weir). Flow rate is not normally influenced by the dimensions of the wetland. A large flow rate will generally mean that a large area of wetland is needed.

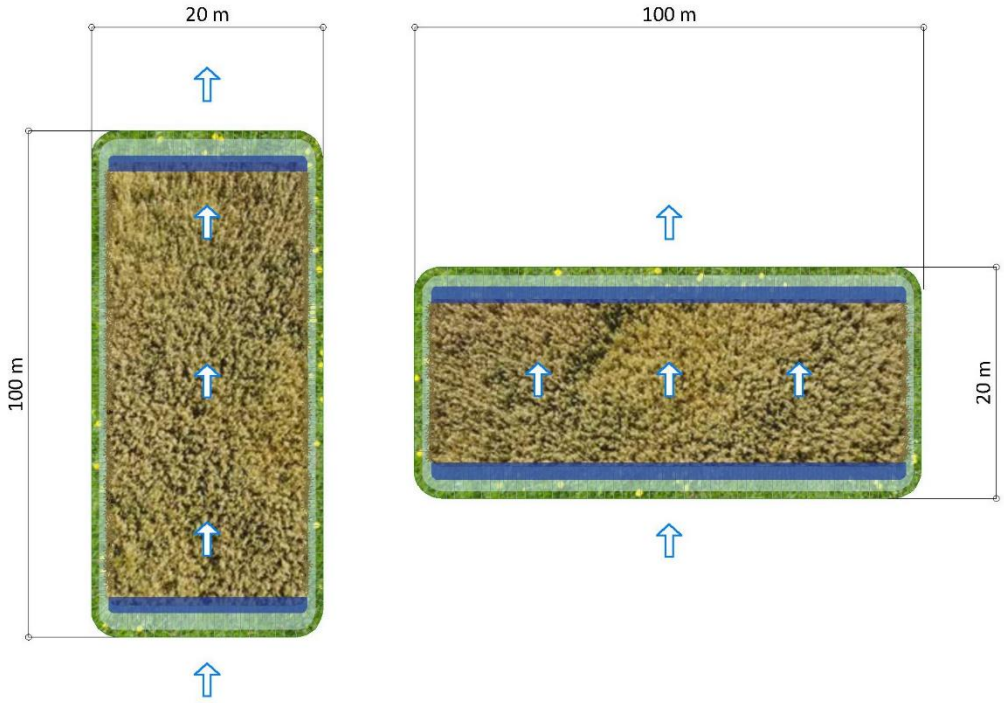
The *Hydraulic Loading Rate* (HLR) is simply the flow rate applied per unit the area of a wetland or wetland cell (so Q/A where Q is the flow rate entering the wetland and A is the area of the wetland in question). It is expressed in units of metres (or centimetres) per day (or per year). It is sometimes helpful to think of these units as cubic metres of water per square metre of wetland per day. When expressed in metres per year, this is the parameter q used in the P-K-C* wetland model in (e.g.) Kadlec (2019). A low hydraulic loading rate will in general deliver better treatment, as long as it is not so low that the wetland dries out.

Hydraulic Retention Time (HRT) (sometimes called detention time or residence time) compares the Flow Rate Q with the volume of water that is stored in the wetland under normal conditions. It is often understood as the length of time that it takes incoming water to displace the volume of water that is normally stored in the wetland. It is calculated by multiplying the area A of the wetland in square metres by the mean water depth (often 0.3 metres) to give the volume of water V in cubic metres and dividing this number by the Flow rate Q in cubic metres per day. The result in this case will be in days. It is important to remember that it is almost impossible to achieve a perfectly uniform flow of water across a free-water surface wetland, and because of this hydraulic inefficiency, a proportion of incoming water will actually spend considerably less time within the wetland than the HRT, and a proportion considerably more time, the HRT is in this sense the “average” retention time. For this reason, it is sometimes called the “nominal” detention time. A large hydraulic retention time will in general be associated with a lower q value in the P-K-C* model, so will be expected to offer better treatment.

The *Velocity* of the water is the speed at which water is travelling in a particular direction in a particular part of the wetland. It will normally be described in metres per second or metres per day. It is an important factor to consider when designing wetland hydraulic performance, and often overlooked. A notional value for “average” velocity of water may be calculated by dividing the flow rate by the cross-sectional area through which the flow is being fed. This cross-sectional area is the depth of standing water in the wetland multiplied by the mean “width” of the wetland perpendicular to the overall flow direction. Designers would generally be looking to reduce velocity to deliver more effective treatment processes and better hydraulic efficiency.

This notional “average” velocity is the factor referred to as “velocity” in the remainder of this section, unless an alternative meaning is otherwise clear from the context. True water velocity will not be uniform even within a cross section of wetland due to factors such as localised channelling of water and frictional effects around plant stems, sediments and leaf litter. Velocity of water may be influenced by controlling the depth of water in a wetland or the width of the wetland perpendicular to the flow path.

FIGURE 5.2 – VELOCITY THROUGH DIFFERENT CONFIGURATIONS OF WETLAND CELL



TWO WETLAND CELLS WITH THE SAME AREA AND DEPTH OF 0.3m, BUT WITH DIFFERENT ORIENTATIN FLOW PATH

STORAGE VOLUME (V) AND HYDRAULIC LOADING RATE(HLR)

$Q = 50\ m^3/d$
$q = 50 / 200 = 0.25\ m / d$

$V = 100 \times 20 \times 0.3 = 600\ m^3$

$HRT = V / Q$
$HRT = (600\ m^3) / (50\ m^3/d) = 12\ days$

CROSS SECTION AREA

$= 20m \times 0.3m$
$= 6\ m^2$

NOMINAL VELOCITY

$V = (50m^3/d) / (6m^2)$
$V = 8.3\ m / day$
$= 1 \times 10^{-4}\ m/s$

STORAGE VOLUME (V) AND HYDRAULIC LOADING RATE(HLR)

$Q = 50\ m^3/d$
$q = 50 / 200 = 0.25\ m / d$

$V = 100 \times 20 \times 0.3 = 600\ m^3$

$HRT = V / Q$
$HRT = (600\ m^3) / (50\ m^3/d) = 12\ days$

CROSS SECTION AREA

$= 100m \times 0.3m$
$= 30\ m^2$

NOMINAL VELOCITY

$V = (50m^3/d) / (30m^2)$
$V = 1.66\ m / day$
$= 2 \times 10^{-5}\ m/s$

The reason that water velocity is important is because it influences the way water interacts with media, sediments and plants in a wetland system, specifically:

- Velocity influences the kinetic energy and momentum of the water. This in turn governs how likely it is that moving water will disturb and remobilise wetland sediments. It is the stabilisation of these sediments that is central to sustainable phosphorus removal in wetlands.
- Lateral deflection of water as it passes through a wetland will be greater if the momentum (hence the velocity) is low. This means that when velocity is low, water will spread out to a greater extent across the width of the wetland, improving the distribution of water across the wetland surface.
- High velocity water may cause scour of growing substrate, particularly in newly planted wetlands.

Designing Wetlands to Optimise Hydraulic efficiency.

It is not always necessary or appropriate for a wetland designer to optimise hydraulic efficiency above other design objectives. Water quality improvement should normally be only one of a number of benefits delivered by a wetland so it is legitimate for the wetland to be optimised for e.g. landscape appeal and engagement, habitat improvement, or flood risk reduction.

There will be project specific opportunities and constraints that are going to influence decisions about the size and shape of wetland cells, and the designer should always be aware of these and adapt the designs accordingly.

The following 13 step approach may in general be a suitable way to integrate hydraulic efficiency with the overall design priorities of the wetlands.

1) Sketch out a plan view of the area that is available for wetlands, taking into account access needs and constraints. Mark borehole and trial pit locations on this plan, with notes about the levels of key strata (this may have already been done during the outline design phase).

2) Make a preliminary decision about the likely inlet and outlet points for the overall treatment wetland system. If quantification of nutrient removal is needed, these points will be a well-defined point of entry and exit for instance a weir, a ditch or a pipe. Consider the level (elevation) at which water may be taken from the source and the level at which water may be discharged.

3) Draw a longitudinal section or hydraulic profile from the inlet to the outlet showing existing ground level, levels of key geotechnical information (e.g. top of clay, bottom of clay, groundwater range), and mark the levels of inlet and outlet on this drawing.

4) Decide upon the number of wetland cells and suitable rest water level and mean water depth in each. This will be influenced by the overall hydraulic gradient across the site and the size of the excavation required to achieve the required land formation. Where practicable it is often advisable to have at least 3 distinct cells in series to restrict the potential for preferential flow paths developing. It is sometimes advisable to have two distinct flow paths in parallel, to allow cells to be closed off if needed during their lifetime for maintenance purposes. It is important to remember though that an increase in the number of wetland cells will increase the overall footprint of the wetland system for a given treatment area (because of the need for bunds between cells), so a compromise may be needed if space is constrained.

5) Sketch the outline of the wetland cells of the required size onto a copy of the constraints drawing, taking into account the existing ground levels, and the required depths of excavation, considering the following guidelines:

- If there is a well-defined target treatment area that is smaller than the overall available area, this preliminary sketch should over-size the wetlands compared with the treatment area by perhaps 20% to allow for hydraulic inefficiency.

- A common rule of thumb is that a target length to width ratio of between 1:1 and 3:1 may be expected to achieve a reasonable compromise between on the one hand improving the volumetric efficiency and reducing the tendency for water to "short circuit" the wetland in fast flowing channels (longer wetlands are better in these respects), and on the other hand keeping velocities low and avoiding undue influence from the "edges" of the wetland cells (so best to avoid unduly long and thin cells).

- It is worth considering a target minimum width of wetland to keep the average water velocity (hence speed) below a target figure. Water speeds greater than around 0.025 to 0.07 m/s are reported to cause resuspension wetland sediments in some circumstances (Larsen et al 2009), Considering that the peak speed may be as much as a factor of 10 larger than the mean speed, 2.5 x 10^{-3} m/s may be considered a suitable target velocity, calculated as:
  $u = \frac{Q}{3{,}600} * 24 * w * h$

  u = mean velocity in m/s,
  Q=flow rate in m^3/d,
  w = width of wetland,
  h = mean target water depth in wetland across the width w (often 0.3m).

  If water passes through the wetland with very low velocity (less than about 2.0x10^{-3} m/s) it will have a lower momentum, and so the flow path is more likely to spread out owing to interaction with emergent plant stems etc, causing better

distribution of flow across the width of the wetland and so improving hydraulic efficiency.

- The width of the water surface should generally be at least 4 metres to avoid the edge of the wetland having an unpredictable influence on flow paths. Mark the intended inlet and outlet points for each cell on the sketch. At this stage the exact shape of the cells will often be designed to suit the landscape fit with the site and surrounding area (optimisation for hydraulics can be done later).

6) Draw cross sections through the proposed cells, showing the existing ground level and key geotechnical information and other relevant constraints. Sketch the profile of the banks and bunds and the proposed water level in the wetland.

7) Take another look at the plan view of the cells and mark up the maximum extent of the base of the banks on this plan (based upon the bank profile that is desired).

8) Consider the shortest straight line from the inlet of the cell to the outlet. This is the direction of the overall hydraulic gradient, and so it is the line along which water will tend to travel unless there is something encouraging it to do otherwise. It can be helpful to sketch a few likely flow paths on the wetland cells between the inlet and the outlet. It is reasonable to expect some deflection/ dispersion of flow by the stems of wetland plants, but never by more than about 45 degrees to the overall direction of a line directly to the discharge point. Depending upon the cell dimensions, it may be appropriate to locate the inlet and outlet points of the wetland cell so that they are off-set to increase the path length and reduce the probability of short-circuits.

9) Consider the “pinch points” of the system, for instance places where all the flow is forced over a weir, through a pipe or along a ditch. In these areas the velocity (and hence the kinetic energy) of the water will be highest. It may be advantageous to introduce features to dissipate the energy of water at these points, to improve distribution and reduce the risk of scour. “Rip Rap” boulders or deeper pools are sometimes recommended for this purpose.

10) It may be advantageous to introduce features to influence the likely flow paths to improve hydraulic efficiency. Such features may include distribution trenches, baffles, and strategic changes to the cell bathymetry. The influence of such features has been the subject of much research and is discussed extensively in Kadlec (2019) chapter 17.2. Some of the key points from the discussion are included below:

a. It is generally considered to be beneficial to have a deeper zone of open water close to the inlet, to act as a “spreader trench” and a deeper zone adjacent to the outlet to be a “collector trench”. These are normally at least 1m deeper than the water in the adjacent wetland. The inlet end “spreader trench” is likely to encourage deposition of incoming sediment (which is normally a useful part of the wetland function). If the incoming sediment load is high, provision will need to be made for silt to be removed from this area.

b. Some designers like to introduce transverse “deep zones” at intervals along the path length to redistribute flow and interrupt preferential flow paths. There is some evidence from hydrological modelling that interventions like these may benefit hydraulic efficiency, though evidence of resulting treatment efficiency is less clear.
c. Baffles or internal berms have been used in wetlands to create a more sinuous flow path. These can be beneficial particularly in irregularly shaped wetland cells, though should be used judiciously. The following considerations are pertinent:

    - Increasing path length in this way will not increase hydraulic residence time. The velocity of flow will increase to compensate for the increased path length at any given flow rate.
    - Features such as this will normally add to the complexity of the build, and hence the financial and energy cost of construction. Any increase in cost needs to be justifiable in terms of the benefits that result from it.
    - Internal earth berms use up wetland area that will no longer be available for treatment. This will need to be accounted for in performance forecasts.

d. Irregular undulations on the base of a wetland are often specified to offer a variable water depth to improve the diversity of ecological niches provided by the wetland. Such variation may also be expected to increase the distribution of flow across the width of the wetland by introducing localised variations in hydraulic gradient that are in a different direction from the overall hydraulic gradient of the wetland cell. The introduction of “hummocks” or “ridges” on the wetland base, into which vegetation is planted is one such example of this practice.

11) Mature emergent and submerged vegetation in a wetland will improve hydraulic distribution. It is important to remember though that in most cases the vegetation will not become mature for several years after planting. This is considered further in the section on ”Vegetation communities”.

12) Make an estimate for the treatment area of the wetlands based upon the likely hydraulic efficiency that has been determined in steps 8-11 above. Only the part of the wetland that is a within an active flow path should be considered treatment area for the purposes of performance calculations. This will ensure that nutrient removal is not over-estimated and will lend some consistency to results of performance monitoring.

13) Consider the opportunities for co-benefits offered by the parts of the wetland outside of the main flow path. It is likely that there will be considerable value in retaining these to offer additional biodiversity or landscape / engagement potential, or to offer storage for to mitigate peak flow to contribute towards wider Natural Flood Management initiatives in the river catchment. This is considered further in the section on “Designing for Multiple benefits”.

Water Depth

The depth of water in a treatment wetland will affect the speed of the water flowing through the wetland. This will in turn affect the way water is distributed in the wetland and the probability of scour and hydraulic short circuiting. Depth will also have an influence upon the plant communities that are most suited to the environment in the wetland and the ecological niches that are supported by the wetland.

A greater depth of water in a wetland will increase the total volume of water stored, and hence the nominal Hydraulic Retention Time of the wetland, however it is generally recognised that (perhaps counter-intuitively) this doesn't necessarily improve treatment efficiency, which is much more closely related to the treatment area of the wetland.

The following considerations are expected to be pertinent when designing the depth profile of water for a treatment wetland:

- Wetland vegetation will not tolerate water depths much in excess of 1 metre. A water depth of 0.1 to 0.3 metres is a common target, as a wide range of submerged and emergent vegetation will grow with a reasonable density.
- Water depth will generally be controlled by first deciding upon a target water level (Normally controlled by structures on the outlet – see section on "Water Management and civil engineering") then specifying a range of levels for the base of the wetland. It may be that the water level (and hence depth) is designed to vary to provide temporary storage in storm events as Natural Flood Management.
- Manual control over the depth of water is often needed, particularly during commissioning when newly planted vegetation may not be tall enough to tolerate the full depth of water. The water control structures should be designed with this need in mind.
- It is good practice to design variation into the water depth. This offers a wider range of environmental niches for different plants and animals. Not only is this greater complexity good for biodiversity, but it is likely to be beneficial for treatment as different organisms (e.g. flowering plants) will be most active at different stages of the season, potentially offering a longer active growing season. A complex bathymetry also offers greater resilience to changing environmental stresses over the lifetime of the wetland.
- Variation in depth over short distances will also add complexity to hydraulic flow paths within the wetland, increasing the dispersion of water as it passes through the wetland. This hydraulic complexity is sometimes done with random variations, or sometimes with strategic "shallow" or "deep" features perpendicular to the direction of flow in the wetland cell.
- Areas of deep water will reduce the velocity of water locally. This will tend to cause sediment to settle out of the water. Settling of waterborne sediments in this way is an essential part of the function of treatment wetlands, and should be promoted, however over time, the settlement will reduce the depth and effectiveness of the

wetland. This effect needs to be mitigated against in the design of the wetlands. The following approaches should be considered:

- Where incoming sediment loads are expected to be high, a “sediment forebay” could be considered, as discussed in CIRIA C753 “The Suds Manual” A sediment forebay is a dedicated deep area of open water immediately adjacent to the inlet of the wetland, often containing features to dissipate energy in the incoming water. These are normally designed so that sediment level can be monitored, and sediment can be dug out of the forebay as needed as a regular maintenance activity.
- The wetland should be designed in such a way that it can accommodate an increase in the elevation of the base of the wetland to a reasonable degree. This should account for sedimentation of incoming water and also the accretion of decaying vegetation as wetland sediments. Kadlec (2019) suggests that an accretion rate of plant matter around 1cm/ year is a reasonable expectation. This should be accounted for by provision of sufficient freeboard in the walls of the wetland cells, and flexibility in inlet and outlet structures to allow the wetland to function as intended even when the base levels rise. see section on “Water Management and civil engineering”.
- Consideration should also be given to providing some extremely shallow gradients (1 in 10 or less) or flat areas either side of the waters’ edge. This will make the wetland more suitable habitat for amphibians and will offer an easier escape for people or animals which enter the wetlands by mistake.

Accounting for head loss within wetland cells.

In all hydrodynamic systems there is a finite loss of hydrostatic head to the frictional forces between the water and the structures through which that water is moving.

The majority of small or medium sized “free water surface” wetlands will exhibit sufficiently low water speeds that the resistance to flow from the sides and base of wetland cells, and from the emergent and submerged wetland vegetation is sufficiently low that it can safely be ignored, and the hydraulic head is negligible over the length of a wetland cell. For larger wetlands however, where path length from inlet to exit is of the order of a few hundred metres or more this assumption may not be a safe one, and water may “back up” at the inlet end owing to the frictional effects of the vegetation. The wetland should be designed to accommodate this increase in level.

A model for checking and estimating head-loss in free water surface wetlands is discussed in Kadlec (2019) chapter 3. Figure 3.1 in this chapter offers a method for estimating the ratio of water depth at the inlet to that at the outlet, by reading off curves against a factor M1 which contains cell length, depth and hydraulic loading rate, as well as a constant that represents the friction offered by the vegetation density. This method is not reproduced here as it is rather involved and is not expected to be a critical design issue for most UK

wetland projects for nutrient removal, where hydraulic loading rates should generally be low (of the order of 0.1m/day).

It is important for the wetland designer to note that if head-loss calculations are needed, the mathematical model offered by Manning's Equation (which is normally the first resort of civil engineers when dealing with frictional head loss) is NOT a suitable model for wetlands and will tend to under-estimate head loss. This is because emergent vegetation will act to resist the full depth of water (so won't be modelled accurately by considering water travelling over a "rough" surface).

Water management and civil engineering

The detailed design must provide solutions to specific challenges posed by the creation of the wetland. The following subsections describe in turn the following challenges and provide outline guidance on the necessary engineering design measures.

- Intake structures;
- Water level control within the wetland;
- Structures to control flow paths within the wetland;
- Managing groundwater;
- Dealing with existing land drains;
- Dealing with unexpectedly high or low flows, blockages etc.;
- Outlet structures;
- Cut and fill balance
- Access for maintenance;
- Erosion control.

Intake Structures.

How will the influent source(s) of water be directed to the wetland, allowing for the design flow rate and ensuring that the wetland is not unduly bypassed?

Intake from a Wastewater Treatment Works

If the source water is from the effluent of a wastewater treatment works (WwTW), a suitable means of diverting the flow from the current outfall will be required. It is desirable for the outfall to be retained for emergency use, so that the WwTW can still freely discharge if and when the flow to the wetland is inhibited for any reason.

An interception chamber can be installed in the outfall pipe, with the outlet to the wetland set at a lower invert level (IL). This ensures that effluent will preferentially flow to the wetland. If the IL of the new connection is too low to allow a passive flow due to the wetland being at a higher elevation, a pumping station will be necessary to transfer the intercepted effluent. The pumping station will typically consist of a wet well with two

submersible pumps (arranged duty / standby). An adjoining storage tank may be required to buffer higher flows and provide storage when the pumps and/or wetland are undergoing maintenance.

The pumping station will deliver intercepted effluent to the wetland via a rising main. The rising main will typically consist of a buried plastic HDPE pipe, routed and sized in accordance with best practise. The rising main should terminate in a connecting chamber, from which transferred effluent flows into the wetland under gravity.

Intake from an Ordinary Watercourse

Flow rates in the watercourse may be estimated based upon the annual average rainfall and catchment descriptors using the UK Centre for Ecology and Hydrology “Low Flows” methodology. This may be sense-checked by flow monitoring. If a higher degree of confidence in flow rates is needed, detailed hydraulic modelling of the watercourse may be required to understand the range of available flow from the watercourse.

Perhaps the most obvious solution would be to use a weir to divert an Ordinary Watercourse through the wetland, however in many situations this will be unacceptable from the perspective of the geomorphology of the watercourse. If this is the case, a “leaky” dam may be more appropriate, in which a limited amount of base flow is allowed to travel through the leaky dam, though flow will be restricted during storm conditions, and the weir will become active.

The height of the weir is critical in creating enough head from the intake channel for gravity flow through the wetland cells (the higher the better). The height of the dam is equally critical with regards to upstream flood risk (the lower the better). It is sometimes a reasonable rule of thumb to set the top of the dam at half the depth of the stream channel to balance risk with performance, checking that both are acceptable, though if there is significant flood risk locally, hydrological modelling of the proposed situation will be necessary. The invert level (IL) of the weir in the intake channel will generally be set lower than the height of the dam, to ensure that flow is delivered to the wetland as needed.

The leaky dam will often be assumed to be impermeable for the purposes of assessing flood risk, to remain conservative. However, the designer must take account of the permeability of the dam when anticipating how much flow can be successfully diverted into the wetland. If the dam is too ‘leaky’, too much flow from the stream will pass entirely through the dam at a depth not great enough to reach the invert of the wetland intake weir.

Additional detail on flow calculations using such a weir is included in appendix – ‘Additional material on weirs’.

Water level control within the wetland

Water levels of individual wetland cells can be controlled using any one of the following structures, immediately downstream of the cell:

- Stop log weir
- Penstock weir
- Swivel pipe

These structures will be set within the berm between successive wetland cells. Consideration of how water passes from one cell to the next will determine how these structures will be arranged.

A stop log or penstock weir can be installed within an open channel or within a weir wall chamber with piped connections, whereas a swivel pipe should only be installed within a chamber with piped connections.

Consideration of how the level control will be operated is also important from a health and safety perspective. Controls within chambers should ideally be adjustable without having to enter the chamber, which is technically a confined space. Penstock weirs with non-rising stems can be operated using ‘tee-key’ handles, with the spindle of the handle inserted through a small opening in the chamber cover. Stop logs typically require some form of lifting apparatus, which will require the chamber to be open. It is possible for swivel pipes to be adjusted by reaching into the chamber, rather than entering it, but it depends on how they are fixed to the connecting pipe. Loose ‘push fit’ plastic fittings can be adjusted simply by hand, whereas flanged fittings will require bolts to be loosened – which means entering the chamber to access the bolts at the bottom of the chamber. Whilst the push fit fittings are more user friendly, they are not as robust as flanged connections, and it is advisable that a chain or other means of securing the pipe is used so that it cannot rotate under gravity once set.

Penstock weirs and swivel pipes allow for an ‘infinite’ degree of adjustment within the level control range, whereas stop logs can only provide a ‘step’ adjustment, with increments of depth dictated by the height of the individual logs. This is important in the context of managing vegetation, both during start up and in the longer term, and also for specific ecological benefits, where finer adjustment may be necessary.

The full level control range should allow for the maximum depth of water to be achieved and ideally for the cell to be drained sufficiently to facilitate de-silting / refurbishment when needed. If full drainage of the bed is expected to be needed, it is advisable for the lowest settable level to be 50 mm below the design level of the bed. The highest settable level should be sufficiently lower than the top of the berm surrounding the cell, to ensure that the minimum freeboard is available.

Control of the flow path within the wetland

A method for controlling the flow through the wetland is sometimes needed so that water can be routed through one or more flow paths, and other cells can be taken off-line.

Specific flow paths can be set using isolating penstocks, either in open channels or enclosed chambers. This can allow individual cells to be isolated and bypassed if needed for maintenance or repair.

One simple measure to regulate the flow through wetlands receiving varying flows is to modify the level control structures at the outlet end of each cell so that they incorporate a contracted rectangular weir.

Whilst any kind of weir will cause the upstream water level to rise as water flows over it (the increased level is known as the afflux), a contracted weir will cause more of a restriction to the flow and therefore the afflux is greater. This can be beneficial where the designer intends for the wetland to make full use of the temporary storage volume afforded by the freeboard within the cells, for the peak design flow. A suggested weir design to make the most of this effect is described under “Designing for Multiple Benefits” section below.

The calculation of afflux upstream of a contracted weir for a specific flow can be made using a standard formula from Chadwick, Morfett & Borthwick, 2004.

It is important to ensure that the afflux for the peak design flow is not greater than the available freeboard (where the freeboard is the vertical measurement from the invert of the weir to the top of the berm). Maximum water level should also be controlled by an emergency overflow, as detailed in “Managing Exceedances and Blockages”.

How will groundwater be managed?

The depth to the water table should have been determined from the ground investigation. This will of course be seasonally variable and is likely to be at its highest in late winter / early spring. Handling groundwater during construction can be complex, costly and will carry pollution risk, so should be avoided. It is normally best to design the wetland so that the lowest excavation is above the groundwater table, with due consideration of other constraints such as flood risk which may limit the maximum level of berms and other structures. If the peak groundwater level is still likely to be high relative to the elevation of the cells, then the detailed design may need to include measures for preventing ingress to the wetland cells.

The use of land drains around the periphery of wetland cells helps to alleviate pore water pressure in the substrate below the cells as the groundwater level rises. Localised areas of high groundwater can be reduced by homogenising the groundwater level over the entirety of the wetland area, by linking the land drains.

If artificial liners are proposed, drainage beneath the liner may be needed if there is a risk of groundwater rising above the base level of the wetlands.

Dealing with existing land drains

Wetland sites on agricultural land often feature historic land drains and ditches, where the land was deliberately drained for agricultural use. Many of these historic systems have fallen into disrepair, with ditches filling up with vegetation and silt above the elevation of the connecting land drains.

Depending upon the nature of the site and the project objectives, it may be advantageous to feed the water from existing land drains (or other surface water drains) into the new constructed wetland to achieve flood mitigation and water quality benefit by mitigating the flow from the drains.

Sometimes there may be a need to keep water from land drains outside of the constructed wetland (e.g. if the nutrient load into the wetland needs to be carefully measured to provide nutrient credits). If this is the case, the land drains can be connected to ditches that are not part of the wetland construction, allowing drainage water to discharge freely without influencing the measured performance of the wetland.

Managing Exceedances and Blockages

All constructed wetlands should be designed to safely accommodate exceedance flows, whether they are caused by extreme storm events (including an allowance for climate change), operator error or the blockage of cell outlets. Overflows from the cells must be conveyed safely downstream, without causing erosion of the berms or accessways. This may mean lowering part of the berm surrounding each cell to create a spillway, directing any overflow into a specific pathway. Cells arranged in series can be designed to overflow through the same pathway (cascading form one to the next), whereas cells adjacent to a watercourse could each have their own overflow directly to the watercourse. Where parts of berms are lowered to create spillways, the designer must keep in mind that the available freeboard within the cell is governed by the level of the spillway, not the top of the remaining berm.

Discharge Structures

Final outfalls from wetlands will consist of an open channel or a piped connection. The detailed design must show how this will connect to the ditch, watercourse or main river to allow the final treated water back into the water environment.

For a piped outfall, this may consist of a headwall set within the bank of the watercourse. For high velocity outlets, the design will need to consider how the backfill of soil around the headwall will be protected from erosion by the water passing through the watercourse. Soil should be reinstated in layers, compacting each one before adding the next and ensuring that the profile of the embankment is sloped at 1 in 3 or less if possible. The diagram below provides a good example of how headwalls should be installed, using a ‘revetment’

constructed from timber stakes and coir matting. The matting is laid over the soil to protect it from erosion whilst allowing for vegetation to grow through it (either planted whips or seeds naturally germinating within the underlying soil). The stakes provide support for the reinstated embankment, preventing slumping into the channel. A rock mattress provides a scour apron to prevent localised erosion from the outfall itself. This ‘formalised’ approach is important for applications in main rivers, where a detailed construction method is required as part of the application for a flood risk activities permit (FRAP).

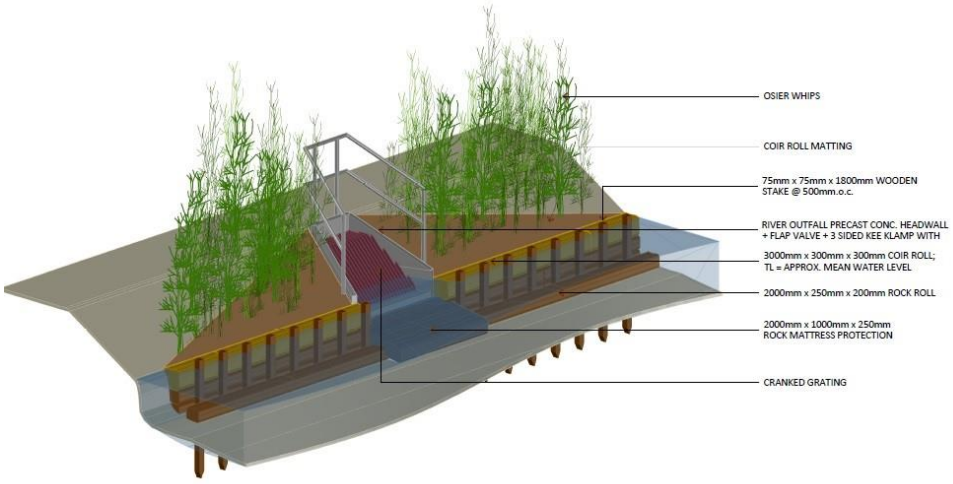


Figure 5.3. Formalised outfall showing erosion protection details.

A more rustic looking solution may be more appropriate for rural sites, as illustrated below.

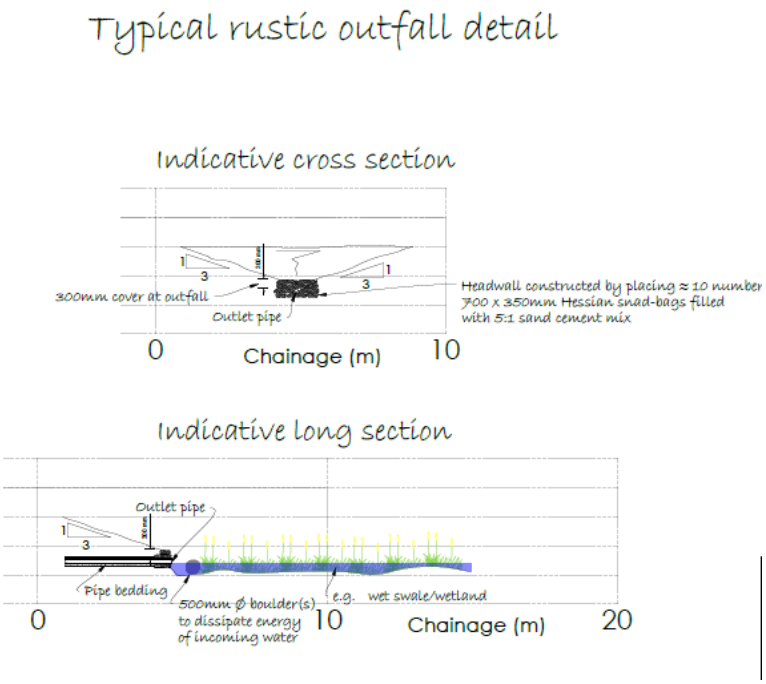
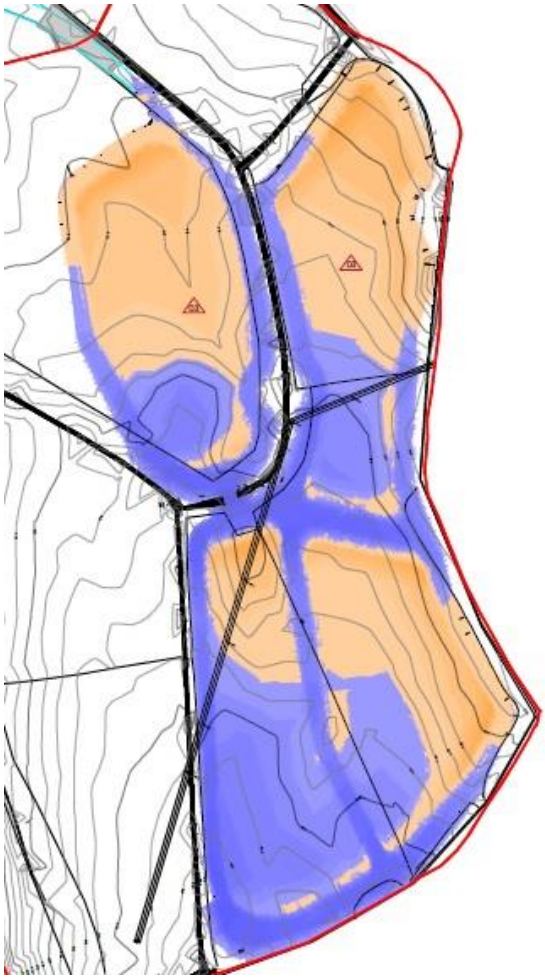


Figure 5.4 Typical rustic outfall detail

Balancing cut and fill.

As with any other construction project, the amount of spoil produced by the earthworks should be estimated using a cut and fill analysis. In its simplest form this may involve looking at the depth of excavation or fill that will be needed in each grid square of the wetland development and summing these up. On smaller projects it may be cost effective to do this process by hand, whereas for larger projects this is typically accomplished with 3D design software, using the topographical survey of the site to create a 3D surface of the existing ground and superimposing the 3D design of the wetland basins. The software then calculates the difference between the existing and design levels to produce a heat map of the cut and fill areas, along with a table of cut and fill volumes on a level-by-level basis.



EARTHWORKS VOLUME			
	HEIGHT BANDS	CUT VOLUME	FILL VOLUME
	1.600m - 1.400m	0.71 m³	-
	1.400m - 1.200m	8.57 m³	-
	1.200m - 1.000m	51.91 m³	-
	1.000m - 0.800m	138.24 m³	-
	0.800m - 0.600m	320.91 m³	-
	0.600m - 0.400m	719.98 m³	-
	0.400m - 0.200m	1220.89 m³	-
	0.200m - 0.000m	1708.67 m³	-
	0.000m - 0.200m	-	1673.56 m³
	0.200m - 0.400m	-	1152.97 m³
	0.400m - 0.600m	-	684.25 m³
	0.600m - 0.800m	-	405.50 m³
	0.800m - 1.000m	-	267.50 m³
	1.000m - 1.200m	-	128.98 m³
	1.200m - 1.400m	-	34.11 m³
	1.400m - 1.600m	-	4.74 m³
	1.600m - 1.800m	-	0.00 m³

TOTAL CUT: 4,169.88 m³
TOTAL FILL: 4,351.60 m³

SPOIL QUANTITY	
EXCAVATED MATERIAL (WITH 1.20 BULKING FACTOR)	5,003.86 m³
FILL MATERIAL (WITH 1.11 BULKING FACTOR)	4,830.28 m³
NET SPOIL VOLUME	173.58 m³

Figure 5.5. Example of cut and fill analysis

Ideally, the cut and fill should be balanced so that there is no need to import or export soil from the site, at least from a volumetric perspective. The designer should apply bulking factors to the estimated volume. These will be based upon the characteristics of the soil which will vary from site to site but will typically be 1.2 for cut volumes and 1.11 for fill volumes.

The designer must also keep in mind any site constraints that will dictate the elevation of the wetland cells and surrounding berms, such as flood risk limitations or overhead services (even if the cells are not directly below them, connecting access ways will need to be ramped to reach elevated berm levels which may require the raising of ground below cables).

The disposal of spoil should have been considered at the feasibility and outline design stages, so the more accurate estimation at the detailed design stage should be checked against earlier estimations to ensure there are not any discrepancies which may hinder disposal. For example, if the intention was for all spoil to be spread on some adjacent land within the same landholding, there may be associated constraints or conditions that limit the volume that can be spread.

How will the wetland be accessed for maintenance?

The type of equipment required to maintain the wetland must be considered at detailed design, to ensure that sufficient safe access to all cells and structures is provided. Knowledge of the access route into the site from the nearest road is also required to ensure that this equipment can get to and from the wetland area.

Vehicular access will typically require routes with a minimum width of 3.0 m. The surface and gradient of access routes must be suitable in terms of trafficability.

The equipment required for maintenance will generally be of an agricultural nature, as management of vegetation within the cells and around the berms is the principal maintenance activity for treatment wetlands. Mowing and strimming equipment may be trailer mounted and towed by a 4x4 vehicle or a quad bike. Less frequent maintenance will require access for small excavators, for the desilting of sediment forebays and/or the repair of berms. Pumping stations will require lifting apparatus to retrieve submersible pumps from wet wells, and the pumps may need to be taken off site for repair. It is therefore reasonable to expect that access for a small van will be required.

Erosion Control

The berms surrounding the wetland cells provide the structural integrity of the cells, enabling them to retain water. They should be formed from excavated soil. Sloping sides no steeper than 1V in 3H are often recommended on the grounds of structural integrity, though it is often better to reduce this to 1 in 4 or less if space allows to offer a more

pleasing aesthetic and more ready egress for people and animals, and 1 in 10 or less immediately adjacent to the water level to provide better egress for amphibians.

Where the berm has to be made above ground level, it shall be built up layer by layer (typically 300mm thick) with each layer being compacted / rolled before the next is added. The designer should consider whether pedestrian access or machine access may be needed along the top of the berms, and if so, a flat crest should be provided of appropriate width.

When first constructed, the berms will be prone to erosion until vegetation is established. If the completion of construction is late in the growing season (October onwards) then it is sensible for coir matting to be used to cover the surface of the slopes and the top. This can be done immediately following seeding, where specific vegetation is required to cover the berm. The matting will protect the soil from rainfall over the winter months until the seeds germinate and establish roots in the following Spring. When designing for vegetative cover to berms, herbaceous plants such as grasses and wildflowers are usually more appropriate than woody shrubs and trees, as their roots consist of a fibrous mat that holds the soil together rather than thick individual roots that may compromise the integrity of the berm.

Bases of channels and areas around inlets and outlets will be subject to faster moving water and will therefore be prone to erosion. Protective measures such as rock rip/rap, scour aprons and rock mattresses should be used to cover soil in these areas.

Vegetation communities

In temperate climates, most emergent wetland vegetation will grow rapidly in the spring and summer months (taking nutrient up into the biomass). In the autumn and winter, the plants will die back, transferring nutrient back into the below-ground parts of the plants, and depositing the dead leaves and stems back into the water where they decay and ultimately become wetland sediment and soil. This decay process will release some of the stored nutrient back into the water, and some will become permanently buried (“accreted”) as wetland soils. This process is an important mechanism for sustainable nutrient removal from water in wetlands.

In addition to nutrient uptake and nutrient release, plants have an important role in flow distribution in Free-Water surface wetlands. In areas where a mature wetland vegetation has become established, the presence of the plant stems will disrupt the hydraulic gradient locally and naturally tend to distribute the flow of the water more evenly. In addition, the below ground parts of the plants will mitigate against the erosive effect of the water on the soil. If a mature wetland can develop, there is a self-sustaining interaction between the plants, the soil and the water flowing through the system. The mature plant communities will form wherever the velocity and depth of water is low enough to allow them to do so.

Mature wetland ecosystems will in general have a beneficial effect upon nutrient removal in a river catchment whether or not they are designed as treatment wetlands. It is therefore extremely important for the goals of nutrient removal, as well as for ecological resilience that the construction of a treatment wetland is sympathetic with the indigenous wetland ecosystems of the catchment, and not cause disproportionate damage to the surrounding ecosystems by (for instance) introducing new, potentially invasive species to the area (whether or not they are native to the UK), or by the action of mechanical plant, access roads, or changes to hydrology.

Choice of plants

- The effect on wetland treatment efficiency of selecting one emergent plant species over another has been the subject of some debate amongst designers and any number of research projects. Broadly speaking, it appears that as long as a dense sward of emergent and/or submerged vegetation can be established, there is little evidence to suggest that the effect of the choice of species has a significant effect on treatment.

- The plants selected should complement the local and regional ecology as well as being native to the UK. This is important from an ecological and landscape perspective, but are also likely to suit the local conditions, including suitability for / resistance to local pollinators and animal communities, which may play an important role in the viability of plants, e.g. pollination, control of pest species. Harvesting and re-use of suitable existing plant stock reclaimed from the wetland site where appropriate is often a good solution though the method of harvest should avoid long term damage to existing ecosystems and control of invasive species. It is wise to seek advice from locally based wildlife charities, Local Authority biodiversity/ countryside team, or scientific and naturalist societies when deciding upon a good plant mix.

- Some designers choose plants with complementary growing cycles so as to help to extend the growing season during which phosphorus uptake is greatest (e.g. choice of plants that flower or actively grow at different times of the year). Conceptually this may help to balance the nutrient demand across the growing season to some degree. A varied plant mix will give the wetland greater resilience against changing environmental conditions, and against plant pests and diseases.

- Consider the conditions in which you are expecting the plants to grow. What is the depth range of water? How much shade is likely? It is normally worth including different species which will tolerate a range of conditions (some shade tolerant, some favour full sun, some deeper water, some marginal) in order that the wetland will be resilient to changing conditions over the decades that we are expecting it to function.

- Plants that are highly invasive and form a monoculture (e.g. Phragmites) do not lend themselves well to a diverse botanical mix, though may have advantages in terms of rapid establishment and high stem density. This may of course be the best choice if there are already established reedbed in the local area, as it is likely that local plants will find their way into the new treatment wetland.

- The inclusion of flowering plants will attract invertebrate pollinators. Not only is this good for biodiversity, but invertebrate movements are conceptually likely to have a beneficial effect in exporting phosphorus from the wetland system.

- It is sometimes appropriate to specify no planting at all in order to allow plants to naturally regenerate within the newly created wetland ecosystem. This has the advantage of ensuring a locally appropriate vegetation mix (providing development of invasive non-native species can be avoided), however vegetation establishment will take longer to complete, and extra care must be taken during the extended commissioning phase that preferential flow paths do not develop within the bare soil. It may be that the wetland is left inundated but with no flow for a period of time until vegetation has begun to develop.

How to make sure the plants grow

Treatment wetland design is a multi-disciplinary undertaking. Civil engineering, process engineering, hydrology, ecology and environmental chemistry are all common backgrounds for designers. It is perhaps surprising how often the importance of horticulture is overlooked! The following points are important:

- Consider the growing medium. Ensure that contractors are aware of the importance of avoiding undue compaction of soils. Many plants will find it difficult to become established in angular gravels or very heavy clays. Topsoil is often good for plant establishment but may leach nutrients into the water for a period after establishment.

- The size of the new plants is important. The larger and better established the plants, the better the chances of success. “Plug” plants will need to be planted at a higher density to account for some loss. It may be suitable to space “Macro-Blocks” directly harvested from nearby sites or established wetland cells by as much as a metre.
- The time of year in which planting takes place has a large influence on the success rate. Wherever possible planting should take place during the active growing phase of the wetland plants’ annual cycle (typically April to August in the UK). If planted in autumn. it is normal to expect some mortality over the first winter, and some re-stocking may be needed in the spring.

- If plants are supplied in compost and planted into mineral soils, it is possible they will become buoyant and “pop out” of the soil once the water level is increased. This is a higher risk when planted outside the growing season.

- Consider the risk of predation from herbivores such as rabbits, geese and livestock. It is normally possible to reduce these risks by maintaining standing water on the bed surface and incorporating fencing into the design.

- Design the wetlands so that control of the water level is possible during commissioning phase. This is discussed further under “Water Depth” and “Water management and Civil Engineering”. And in the “Construction and Commissioning” sections of this guide.

Planting Patterns

It is common to specify a continuous planting density for plants throughout the wetland. Planting density will vary depending on the species and the size of the plants. 3 or 4 plants per square metre is often considered appropriate for emergent macrophytes such as Iris, Typha or Phragmites if they are supplied in 100ml pots or similar.

- “Plug” plants will need to be planted at a higher density to account for some loss.

- If larger “Macro-Blocks” are dug out from nearby sites or established wetland cells, it is normally appropriate to allow a larger spacing between blocks. If there is a robust root/ rhizome mass within the macro- blocks, it is sometimes beneficial to plant these in continuous “ridges” across the wetland cells perpendicular to the direction of flow, to discourage preferential flow paths from developing in the newly planted wetland.

- Planting patterns should avoid large gaps (e.g. between rows) parallel with the flow direction, as these will encourage preferential flow paths.

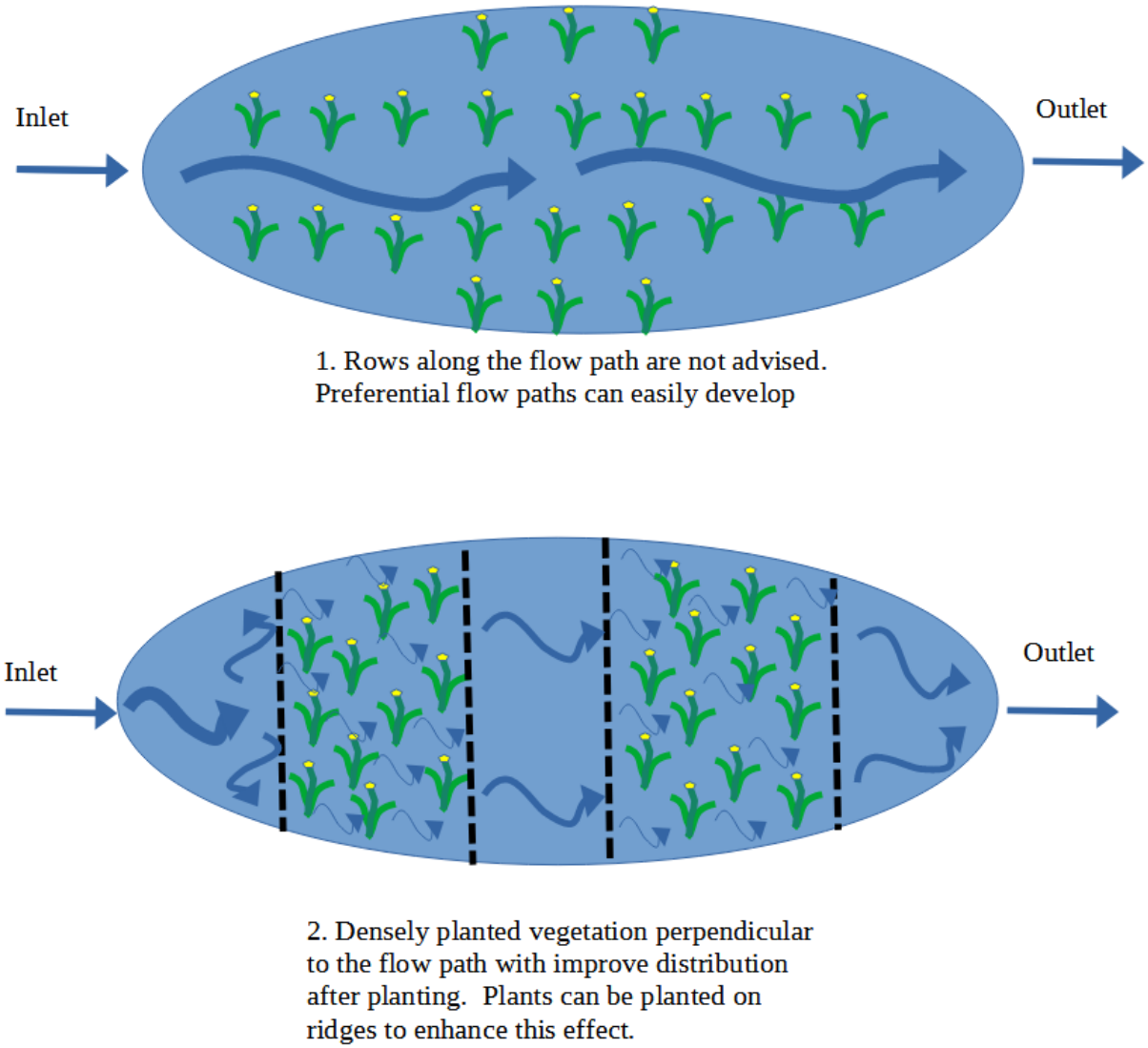


Figure 5.6. Planting Patterns

Soils

Infiltration rates and artificial liners

The permeability of the soil at the site should be known from falling head soakage tests, undertaken as part of the ground investigation. If a range of values are reported, then the precautionary approach is to take the highest where groundwater protection is an issue.

Treatment wetlands intended to improve treated effluent discharge in line with the Environment Agency's Regulatory Position Statement RPS 260 must have a substrate with a maximum permeability of 1 x 10^{-8} m/s, regardless of the wetland water budget. If the measured permeability is greater than this, the wetland cells will need to be lined.

If the water in the treatment wetland is low risk to the surrounding environment, the underlying permeability of the soil should be referenced against the rate of infiltration used in the wetland water budget, which will have been assessed earlier in the project, and the water budget revisited with reference to the measured permeabilities of the underlying soils.

Where lining is required, there are a number of options for materials including:

- Puddling of site-won or imported clays
- Plastic liners (UPVC, HDPE)
- Rubber liners (Butyl, EPDM)
- Geosynthetic Clay Liners (GCLs)

For large FWS wetlands, plastic and rubber materials are not recommended. This is because they are expensive, prone to puncturing and their impermeable composition prevents natural gases within the subsoil (which may occur from decomposing organic material) from escaping to the atmosphere. Clay materials are generally preferable as they can self-heal with regards to punctures.

Puddling clay may be a suitable option if there is sufficient clay on site, but careful consideration of how much is required is critical. The thickness of clay needed will be dependent upon the hydraulic conductivity that needs to be achieved and the risk to groundwater protection that is appropriate to the effluent type. If suitable clay is not available on site, it may be necessary to use a GCL. These consist of a layer of natural sodium bentonite clay confined between a woven and non-woven geotextile, needle-punched together. The thickness of the material is typically only 6 mm, but the performance is equivalent to puddling clay in terms of permeability, due to the purity and homogeny of the clay layer. The material is fabricated in sheets which are supplied in rolls, typically measuring 5 m wide by 40 m long. The sustainability of GCLs needs to be considered, as sodium bentonite is typically mined in China, India or the USA and the manufacturing process for the liners consumes additional resources. Clearly native clay is a more sustainable option if available.

Figure 5.7. Example of GCL being laid out and covered by compacted soil. Photo courtesy of Water Design Engineers Ltd

When designing for GCL lining, it is important to understand that it requires cover with 300 – 500 mm depth of compacted soil. The photo above shows GCL material being laid out and covered. The edge of the GCL at the top of the sloped berms around the periphery of the individual cells consists of an ‘anchor trench’, which prevents the liner from creeping downslope over time. The maximum slope of berms to be lined with a GCL is typically 1V in 3H, as the backfill material will be prone to sliding off the liner on steeper inclines. The following photo shows the anchor trench along the top of the berm to the right of the picture.

Figure 5.8. Photo courtesy of Water Design Engineers Ltd

Planting Media

The other key function of the substrate is to provide rooting medium for the emergent vegetation growing in the wetland cells. Site won soils are often prescribed to form the rooting soil. It is important to avoid undue compaction of soils. Many plants will find it difficult to become established in angular gravels or very heavy clays. Topsoil is often good for plant establishment but may leach nutrient into water for a period of time after establishment.

If a geosynthetic clay liner (GCL) is used, a suitable depth of growing medium (typically 200mm or more) should be added on top of the compacted overburden. If for some reason it is impractical to do this, it is possible in some situations to use this overburden as a planting medium, though specialist advice should be sought about preparation of the overburden with a rotavator to make it suitable for plant growth without compromising the integrity of the GCL.

Designing for multiple benefits

In general, most wetlands ought to be able to deliver multiple benefits to the landscape, amenity and wildlife, and many will be able to be designed to reduce flood risk in addition to performing a treatment function. Designs that consider only treatment efficiency are not good designs unless there is a compelling argument against offering additional benefits, as the additional cost incurred when delivering these additional benefits is generally small.

Amenity and Biodiversity

CIRIA C753 “The Suds Manual” contains guidance on designing sustainable drainage features (including ponds and wetlands) to achieve amenity and biodiversity benefits alongside water quantity and quality. The guidance that follows has drawn upon the CIRIA C753 guidance adapted by specific considerations regarding nutrient treatment wetlands.

The SuDS Manual uses the phrase *“creating and sustaining better places for people”* to capture the essence of delivering amenity benefits. In practical terms, for treatment wetlands, designing to achieve amenity normally entails allowing people to access or engage with the site, and enhancing the quality of that engagement experience.

Landscape Fit

One of the first considerations when deciding the overall layout of a new wetland will be the way the wetland fits into the landscape of the area. This will often be determined by considering the topography of the site and the lines of existing features that will be retained. These may be local watercourses, but they could be manmade field boundaries. Arbitrary curvilinear features set within a flat patchwork field system can look just as out of place as a rectangular wetland within the curves of a “natural” landscape.

The shape of wetland that results from consideration of landscape fit will often not be the most hydrologically efficient shape. This can be corrected by (for instance) designing a slightly deeper “treatment area” within the overall wetland area. The areas outside the main treatment area can be retained as a shallower wetland margin to deliver biodiversity and in many cases additional flow balancing/ natural flood management. It may be best in some cases to reduce the gradient of wetland slopes in the non-treatment areas to achieve a more naturalistic fit for the wetland into the landscape.

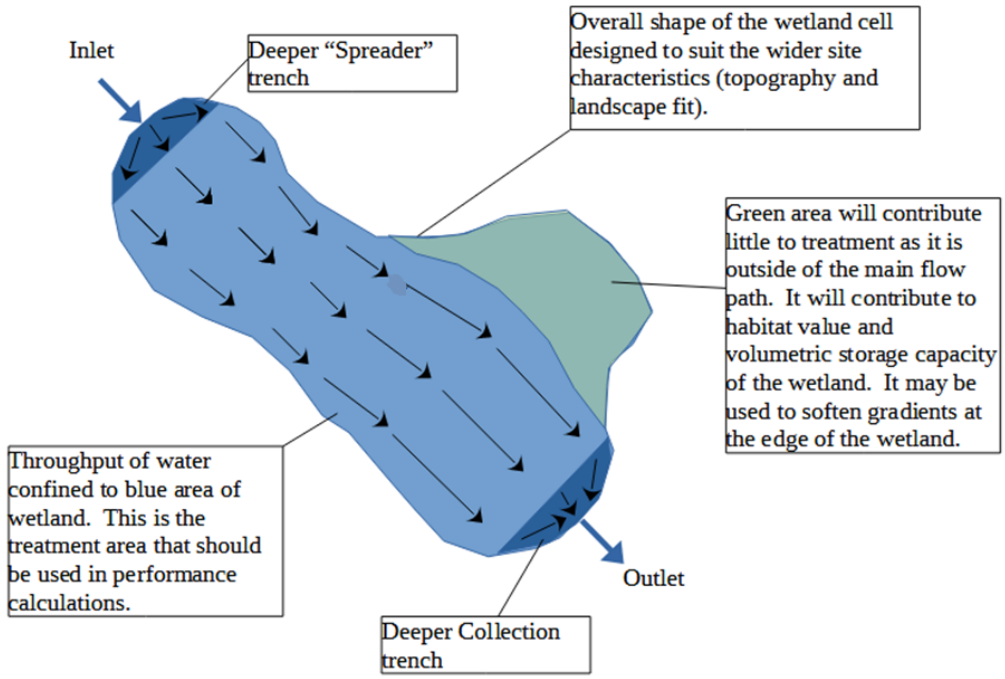


Figure 5.9 – overall wetland area and treatment area

In addition to the wetland area itself, the landscape fit is dependent upon the design of the bunds and marginal areas around the wetlands. Attention should be paid to the gradients and landscaping of these areas. There may be opportunities to create satellite ponds or scrapes in these areas. It may be appropriate to consider finishing these areas as wet grassland or wildflower areas with species suitable for the locality. Herb rich grassland areas may be sown or allowed to regenerate from site-won turves or soil. This will typically require less intensive maintenance than conventional amenity grassland, and if designed carefully they should offer additional visual appeal and wildlife habitat.

Accessibility

Amenity design must allow public engagement with the site. The greater the engagement and the more positive the experience, the better the amenity design. Engagement will normally mean providing some level of access to the wetlands. To provide a high-quality experience, a balance will need to be sought between the total area that is accessible and the need to retain a "wild" character to the site, with provision of safe habitat for wildlife which is inaccessible to humans (and/ or dogs).

There has been a historical tendency for urban pond and wetland projects to include fences and warning signs around all water features. These greatly detract from the public enjoyment of "wild" areas and should be avoided unless there is no other practicable way of reducing risk to an acceptable level. Wetlands are a part of the natural landscape, if well designed they will present a lower risk of drowning than (for example) rivers, lakes or canals, and there is generally no need to restrict access on safety grounds unless the water being treated is particularly noxious.

Fences will be needed in some instances to prevent livestock or other herbivores damaging the wetlands. In those cases, it will generally be preferable to set the fence back from the edge of the wetland feature, to allow some public engagement with the wetland from the inside of the fence.

Public access to wetlands is a desirable aim, so it is necessary to consider public safety in the features themselves. Consideration should be given to designs that will restrict the possibility of people entering the deeper water areas inadvertently, and to provide a ready means of safe escape from the wetland areas for humans and animals. A common safety feature is to provide gradual slopes at the edge of a wetland that can be readily navigated (1 in 4 slope gradients is common) along with a “flat but wet” (<1 in 10 slope) shallow area around the edge of the wetland. This marginal shallow water zone also provides benefit as landing areas for wild animals e.g. amphibians.

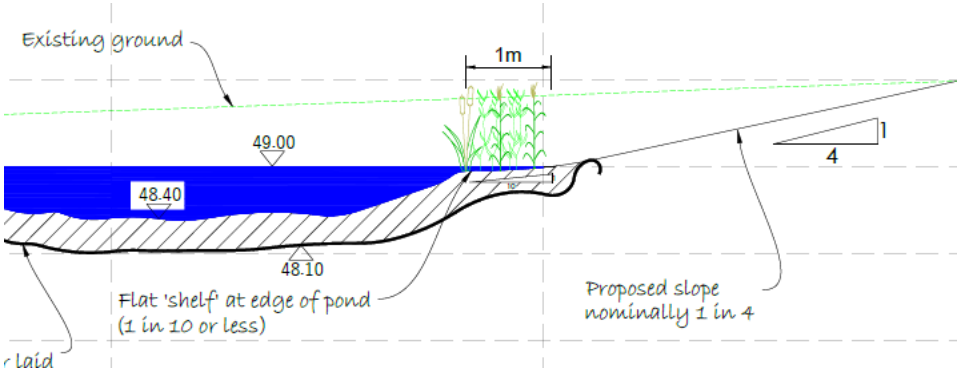


Figure 5.10 – wetland edge profile

If it is decided that open public access is not desirable for a particular site, consideration should be given to offering controlled access for particular interest groups, for instance schools or scientific societies.

Biodiversity

It is good practice to design variation into the water depth by having an uneven base to the wetland. This offers a wider range of environmental niches for different plants and animals. Not only is this greater complexity good for biodiversity, but it is likely to be beneficial for the performance of the wetland, as it offers greater resilience to changing environmental stresses over the lifetime of the wetland. This complexity may be continued in marginal wetland areas outside of the main treatment area, where “hummocks” above the normal water table will offer additional habitat diversity. Irregular shapes to the wetland edge and the presence of smaller “satellite” pond and wetland areas outside of the treatment area will improve the habitat of the overall site.

Non-native species should be avoided within planting plans. The plants selected should complement the local and regional ecology as well as being native to the UK. Such plants will offer greater value to the wider wetland ecosystems, and will be likely to better suit the

local conditions, including suitability for / resistance to local pollinators and predating animal communities. Harvesting suitable plants from elsewhere on the site, and regeneration through the seedbanks in local soils is often a good solution though the method of any harvest should avoid long term damage to existing ecosystems and control of invasive species. It is wise to seek advice from locally based wildlife charities, Local Authority biodiversity/ countryside team, or local scientific and naturalist societies when deciding upon a good plant mix.

It is sometimes appropriate to specify no planting at all in order to allow plants to naturally regenerate within the newly created wetland ecosystem. This has the advantage of ensuring a locally appropriate vegetation mix, providing development of invasive non-native species can be avoided.

Avoid smooth finished surfaces commonly seen in ditch and drain edges, retaining walls etc, as these “tidy” edges do not encourage habitat development.

Consider opportunities for providing or retaining dead wood in dry or wet areas within wetland or the wider site. Dead and decaying wood is valuable for mosses, lichen and fungi. It is also particularly important for invertebrates, as many species rely on it for completing all or part of their life cycles. Decaying wood also offers a long-term carbon source to support denitrification. Standing deadwood if retained can also provide cavities for birds and bats for breeding and roosting.

Flow attenuation / Natural Flood management

If fed by a water source that is influenced by surface water catchments, wetlands will offer an opportunity to slow the rate of peak discharge of water during storm events by providing temporary storage. In order to do this effectively, the water control structures should offer some restriction to flow, and the wetland be designed with freeboard in order to allow the water level to increase temporarily.

There are many potential methods of restricting flow. Including orifices and hydrobrakes. Some of these are discussed in the section on Water Control and Civil Engineering.

It is outside of the remit of this document to provide detailed guidance on storm attenuation, the reader is referred to The SuDS Manual for detailed guidance on this topic.

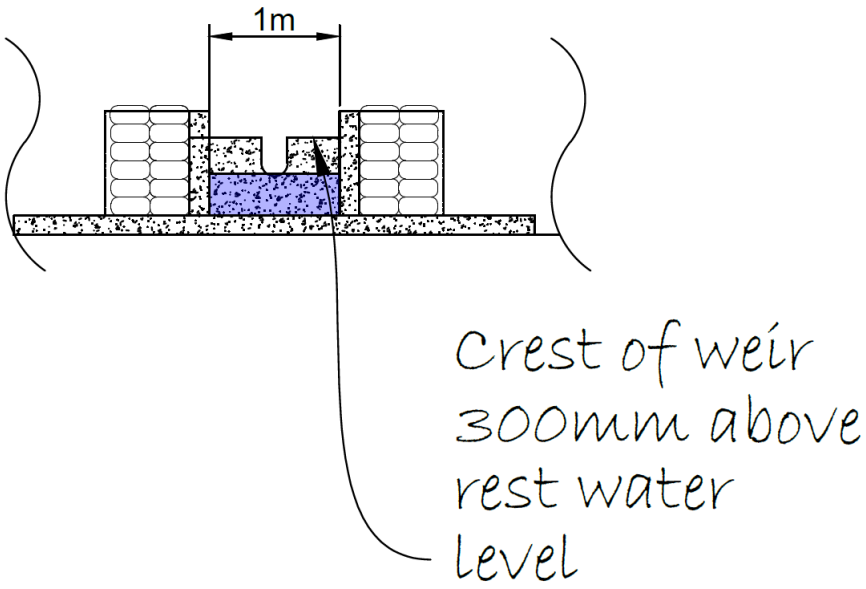


Figure 5.11 Weir designed to achieve temporary storage during storms

Design stage risk assessment

- The Design Risk Assessment (DRA) is to be completed at the **pre-construction** (design) phase of the project, providing a summary of all **hazard avoidance and risk minimisation (HARM) measures** that have been incorporated into the design. In keeping with **Construction Design and Management Regulations (CDM) 2015**, the design **must** consider the potential hazards associated with the entire lifespan of the project – including the processes of construction, commissioning, operation, maintenance, decommissioning and demolition. These processes are grouped into three separate 'phases': Construction; Operation & Maintenance; Decommissioning.
- For each identified hazard, the DRA must clearly show who might be harmed and how, with details of measures and features incorporated into the design to minimise risk and details of any residual risk that remains. Reference to specific design drawings, surveys and reports should be made to provide clarity on the nature of the hazard and the mitigation measures.
- An example of a risk assessment template can be found here: https://www.hse.gov.uk/simple-health-safety/risk/risk-assessment-template-and-examples.htm
- Further details regarding the legal duties of designers within the context of CDM regulations can be found here: https://www.hse.gov.uk/construction/areyou/designer.htm

Sustainability

The following considerations are key to making sure that the wetland project is sustainable, in terms of cost and environmental impact:

- Construction phase – choice of materials, ease of construction. Locally sourced timber is preferable to concrete wherever possible (e.g. timber dams). Concrete pipes have less embodied carbon than HDPE plastic pipes.
- Operation and maintenance phase ease of maintenance. Frequency of desilting activities must be low (ideally 10 – 20 years). Electrically powered pumps should only be used if absolutely necessary. De-commissioning phase. Removal and disposal of concrete, plastics and liners is clearly more energy intensive than wood and clay.

Construction and commissioning

Using the Treatment Wetland detailed design information, a technical specification and environmental management plan should be produced that provides all necessary information for a contractor to undertake construction of the Treatment Wetland. Typically, this would include information outlining the site-specific risks in terms of safety and health, the environment, waste management and incident management. It should also provide information regarding site clearance, earthworks, infrastructure and planting and appropriate method statements.

Site clearance

A construction environmental management plan and corresponding method statements should be produced. These should outline the suitable methods and environmental management plan for site clearance and earthworks, spoil disposal, infrastructure construction and waste disposal to ensure:

- biodiversity features are not detrimentally impacted,
- trees are protected,
- soil compaction is minimised,
- potential pollution incidents are avoided,
- buried services are protected, and
- topsoil and subsoil are handled separately (where needed) and for the suitable disposal of any surplus spoil.

If spoil is to be generated, then it should be identified how this will be handled and where it will be placed at the site or taken offsite.

It is important that there are also an incident management plan and a waste management plan detailing appropriate methods to deal with spillages, flooding, services damage, damage to habitats and species or poor waste disposal and storage and actions required in case of an accident or health and safety emergency.

The following gives an indication of the typical topics to be covered when specifying site clearance:

- Identification of sensitive habitats and species and exclusion zones including timings to avoid bird breeding season for example.
- Identification and exclusion zones for services.
- Vegetation removal – method for vegetation removal and disposal if required.
- Tree protection – size of protection zone and excavation method.
- Topsoil stripping – depth of topsoil to be stripped and method.
- Handling of topsoil and storage – handling requirements and storage location.
- Unstable ground – requirements of contractor if earthworks become unstable.

- Unrecorded features – requirements of contractor if unrecorded features are identified.
- Excess excavation – approach to backfilling and reinstatement.
- Water management – drainage and pumping (if required).

Hydrological commissioning

It is essential that the Treatment Wetland holds water to provide full treatment before water is discharged into the environment. A hydrological commissioning plan should be developed and included within the technical specification for the contractor.

Information should be provided regarding how hydrological commissioning should be undertaken to demonstrate that the wetland holds water before full operation is undertaken. This may include, for example, pressure testing of seals around pipework, permeability substrate tests if using a natural product such as clay or liner testing by gradual filling to determine whether there are any leaks. In particularly sensitive environments, such as overlying a chalk aquifer, it might be appropriate to instal lysimeters under the wetland to detect any potential leaks.

Vegetation establishment

Treatment wetland vegetation can be established through planting, introduction of wetland turfs from donor sites and through natural colonisation. Planting and the introduction of wetland turfs results in an operational treatment wetland over a shorter time frame (one growing season) than if the system is reliant on natural colonisation.

The water levels and maintenance of hydrological inputs has implications for the successful establishment of the wetland plant communities and their future management. Once established correctly, emergent vegetation will be able to withstand the natural seasonal fluctuations in water level. However, young plants are less tolerant of flooding and drought. Some young wetland plants installed at the extremes of their range of life are likely to be lost. If the vegetation communities are not well established after the first year’s growing season, supplementary planting is required. Supplementary planting should mirror the initial planting plan and focus on any particular plant species that has suffered from high losses.

Vegetation establishment - The technical specification should describe in detail the vegetation establishment method. It should be clearly stated how vegetation establishment will occur (planting, wetland turfs from a donor site or natural colonisation) and the timeframe required for suitable plant establishment.

Planting plan - A planting plan should be provided if natural colonisation vegetation establishment is not adopted, identifying the location and planting density of different plant

species or plant communities to be used and an indication of the typical water level range required for each species. To ensure minimal impacts on local biodiversity it is important that native species of local provenance, planted to mimic natural communities found within the catchment, are specified.

Protection measures. Plants can be eaten or damaged by bird and mammal species during establishment so suitable protection measures, if required, should be identified such as barrier fencing and the use of ticker tape between barrier fencing to deter birds flying into planted areas.

Plant die-back and disease loss - Plants can naturally die-back or be lost through disease. Regular checks are required to monitor plant establishment. If plants are lost, then supplementary planting would need to take place.

Supplementary planting plan - Losses of some plants is inevitable so a plan for regular checking and supplementary planting should be provided.

Water levels - Water levels vary for the vegetation establishment phase to the operation phase of the treatment wetlands. It is important to provide guidance within the technical specification and management plan for establishment phase water depths and operational depths.

Consideration of constraints

During the feasibility stage a series of site and construction constraints would have been identified and should be included in a design risk assessment developed during the project. If there are specific issues regarding these constraints, they should be addressed within the technical specification for the contractor. For example, there might be specific access issues for site traffic and plant, there might be site slope issues that might pose a risk for safe operation or there might be specific hydrological management that is required.

Management plan

For a Treatment Wetland to provide effective treatment into the future there needs to be a robust management plan in place that fully covers the routine operation and maintenance of the Treatment Wetland and identifies accident emergency measures if required. Typical topics that are included within the management plan are detailed below.

Operator’s roles and responsibilities - The management plan should clearly identify the roles and responsibilities of the operator and other stakeholders. It should provide contact information, particularly with respect to emergency procedures, if they are required. The management plan should identify the key roles and responsibilities related to the Treatment Wetland. An example of the type of information that should be included is given in the table below.

SITE DETAILS		
Address:		
Postcode:		
SITE CONTACTS	Office Hours (specify)	**Out of hours**
EMERGENCY SERVICES	Office Hours	**Out of hours**
Emergency:		
Medical:		
Police:		
Fire:		
REGULATORS	Office Hours	**Out of hours**
Health and Safety Executive (HSE):		
Local Authority:		
Environment Agency (General):		
Environment Agency (24 hour emergency hotline):		
UTILITY AND KEY SERVICES	Office Hours	**Out of hours**
Specialist advisors:		
e.g. sludge removal contractor:		
OTHER KEY CONTACTS	Office Hours	**Out of hours**
Adjacent landowners:		
Neighbours:		

Table 6.1. Example wetland management plan

Routine operation and maintenance - All routine operation and maintenance tasks required for safe and effective operation of the Treatment Wetland should be included within the management plan. These include, for example, the following:

- Silt management – regular checks using physical measurement of silt depths should take place to determine silt built up within Treatment Wetland cells. If silt levels reach a pre-determined level that affects the hydraulic efficiency of a wetland, then measures should be identified for how silt should be removed from the cells with minimal impact on downstream aquatic receptors.
- Water quality monitoring - phosphorus release can be impacted by resuspension of silts but also changes in the redox conditions in the bed and equilibrium concentrations. Water quality exiting the wetland should be analysed to check if the wetland may have changed from sink of P to source. If the wetland is consistently demonstrating P release, the phosphorous content of the bed substrates can also be checked to determine whether the current capacity of the Treatment Wetland reaching saturation. If it is becoming a source of P, then actions should be taken to increase the sorption potential of the Treatment Wetland (see 'Adaptive Management').
- Water control structures – if water control structures are used within the Treatment Wetland these need to have operational guidance for routine operation and include operation for drought and storm event management. They also require regular maintenance checks to ensure effective operation.
- Pipework and connector ditches and swales – pipework and connector features that deliver water from one Treatment Wetland area to another require regular maintenance checks to ensure they are flowing correctly.
- Bed and bank maintenance – bed substrates and banks vary in the material used for construction from soil to clay to artificial materials. Depending on the type of material used they may require regular maintenance checks. A particular issue is burrowing animals, so regular checks are needed to ensure the system does not leak and if a leak is identified remedial work is actioned.
- Vegetation establishment – the operation and maintenance measures for establishing vegetation within the Treatment Wetland and for monitoring vegetation loss and providing supplementary planting is required.
- Vegetation management - vegetation management is crucial to establishing the habitats and achieving the objectives. Treatment wetlands often undergo natural succession as the communities become established. It is important to maintain the necessary water storage capacity and the desired plant communities, so some regular management is often required. To hold succession at a given stage a vegetation maintenance programme should be produced. This should include the following typical management activities: removal by hand (saplings), cutting and grazing. It is important, for biodiversity management, that the cutting and grazing activities are done on a rotational basis rather than complete removal of all vegetation. Typically, only a third of a bed is cut in any year. Vegetation

management is often required of the beds themselves and the banks of a system. It is important that the removal methods are stated, and that the vegetation disposal location is identified so that material does not fall back into the treatment cells.

- Invasive plant management - invasive plants can be a problem as they can quickly dominate a habitat at the expense of other plant species and compromise treatment performance. They include aggressive native species, such as duckweed, as well as non-native invasive species. Maintenance activities for the identification and removal of any invasive/highly competitive native species and non-native species should be stated. Suitable methods for removal of native invasive/highly competitive species such as Willow spp. saplings includes manual removal whilst winter flooding, cutting back or topping is effective at controlling flood-intolerant plants, such as Willowherb Epilobium spp., Nettle Urtica dioica and Thistle Cirsium spp. For highly invasive non-native species, such as New Zealand Pigmyweed *Crassula helmsii,* Floating Pennywort *Hydrocotyle ranunculoides*, Parrots Feather *Myriophyllum aquaticum*, Water Fern *Azolla filiculoides*, Japanese Knotweed *Polygonum cuspidatum* and Himalayan Balsam *Impatiens glandulifera* manual removal is often the preferred method as the use of herbicides can easily be washed into watercourses and may kill native aquatic flora and fauna.

Emergency maintenance - All environmental hazards, the risks associated with these and an accident management plan setting out how to prevent accidents but also what to do if they occur, should be provided within the management plan. Typical accidents include the following:

- Spillages - where wetlands are overloaded, as a result of poorly carried out maintenance, such as silt removal, where damage to the liner or impermeable substrate accidently occurs or as a result of slow seepage leaks via damaged bunds,
- Flood – storm events greater than the design storm and flooding from adjacent waterbodies or overland, and
- Bank failure – failure of Treatment Wetland bed infrastructure due to land movement, impact, corrosion etc.

It is important that all contacts that should be notified in case of emergency are listed within the management plan. An example register of possible risks and hazards that could be included within the accident management plan is given below:

Possible accident	What would the harm to the environment be?	How do we reduce the chances of it happening?	What to do if it happens
Spillages			
Overloading of settlement pond and wetland treatment system.	Contamination of land, drains, groundwater and watercourses.	If any changes are to take place to the site then ensure settlement pond and wetland treatment system are still large enough.	Follow the spill response procedure as below: Turn the system off at the bypass valve, thus stopping flows; Ensure PPE (Personal Protective Equipment) worn when handling any waste or making repairs; Identify necessary repairs & any potential pollution of the environment; If a spill is not contained, inform the Environment Agency; and Complete repairs and ensure adequate standard before resuming system operation.
Spillages during de-sludging of the facility.		Ensure pipe integrity has been tested prior to use and operator observes de-sludging process.	
Slow seepage of liquids from the settlement pond and wetland treatment system. **NB: Slow seepage can be less noticeable than 'spills'.**		Integrity of the settlement pond and wetland treatment system will be tested as part of the management and maintenance plan. Settlement pond and wetland treatment system will be maintained in line with designer's instructions and management and maintenance plan.	
Failure of Plant or Equipment			
Releases of untreated sewage due to faulty pipe work, blockages, pump failure or liner failure.	Contamination of land, drains, groundwater and watercourses.	Visual inspection and completion of weekly inspection checklist record as part of management and maintenance plan to ensure that septic tank is not passing solids or is over full, the liner is not punctured, and the beds are still holding water.	**Spill response procedure as described above.**
Flood			
Storm event greater than that designed to cope with (1 in 100 year + 40% storm event).	Contamination of land, groundwater and watercourses with untreated sewage and flood water.	Ensure that no surface water/floodwaters from surrounding catchment area can enter the wetland treatment system.	**Flood procedure describing what to do in the event of a flood warning such as installation of barge boards, use of sandbags.**
Failure of Containment			
Failure of containment facilities due to land movement, impact, corrosion and so on.	Contamination of land, drains, groundwater and watercourses.	Visual inspection and completion of weekly inspection checklist record as part of management and maintenance plan to ensure the liner is not punctured and the beds are still holding water.	**Spill response procedure as described above.**

Vandalism			
Unauthorised entry and tampering or malicious damage to property, plant and equipment.	Contamination of land, drains, groundwater and watercourses.	Secure wetland treatment system. Key parts of the system are fenced and access is controlled.	Spill response procedure as described above.

Table 6.2. Example accident management plan

Within the management plan a detailed checklist of routine operation and maintenance tasks, and emergency procedures should be developed as illustrated in the example below:

		Daily	Weekly	Monthly	Quarterly	Annually
1	Walkover inspection check (all relevant staff aware of potential issues)	**x**				
2	Remove rubbish from final wetland cell to prevent blockages to the outlet		**x**			
3	Adjust water levels in response to rainfall events and flooding (**A**) or dry spells, droughts and low usage (**B**)	**A**	**B**			
4	Check settlement pond for sediment levels via measurement. When sediment is within 200mm of the wetland cell bank at predefined measuring point then arrange desludging				**x**	
5	Check relevant pipework and outlets for solids accumulation and blockages. Flush and/or brush out as necessary.			**x**		
6	Vegetation management – surrounding banks and grassland areas strimmed annually to promote wildflower and natural grassland community formation with high biodiversity. Cut in late summer/early autumn					**x**
7	Vegetation management – monitor and remove invasive aquatic species (**A**). Removal of tree saplings, rough cut bund vegetation and bed divisions (**B**). Note that algal blooms are common due to elevated nutrients and that this should not be considered an issue				**A**	**B**
8	Vegetation management (Reedbed) – Once reed is established (Autumn Year 3) an annual rotational cut of the reed should begin in a 3-year rotation. A third of the bed area containing reed should be harvested and the material removed for composting.					**x**
9	Vegetation management (Ponds) – maintain open water areas within natural habitat ponds by selective cutting and removal of arisings in autumn.					**x**

Table 6.3. Example checklist for routine operation and maintenance tasks

Associated with the checklist a maintenance record sheet should also be completed. An example checklist is provided below:

Year 1	Daily walk over inspection							Weekly checks	Monthly checks	Quarterly checks
Quarter 1	1	2	3	4	5	6	7			
Staff initials										
Staff initials										
Staff initials										
Staff initials										
Staff initials										
Staff initials										
Staff initials										
Staff initials										
Staff initials										
Staff initials										
Staff initials										

Table 6.4 Example maintenance record

Monitoring, operation and maintenance

Baseline monitoring

Baseline monitoring should be used to characterise the existing water quality of the receiving water body before a new Treatment Wetland is built. This means setting up a working hypothesis, based on the local situation and the known water quality and quantity, to determine the variability of flow, load and therefore concentration. This hypothesis should be used to identify the baseline monitoring that is required.

Chronic sources of pollution are typically less variable than event-based acute pollution. Chronic pollution from a point or diffuse source should be monitored at regular intervals using a rolling average e.g. effluent from a sewage treatment works or nitrate leaching from agricultural land.

Event-based pollution can be highly variable and should be monitored on a case-specific basis. For point sources a typical event would be an increase in population due to seasonal tourism. For diffuse sources an event might be heavy rainfall that triggers an increase in phosphorus by mobilising pollution from surrounding land. In both cases baseline monitoring data should include a number of these events if the influent concentration is to be characterised accurately.

Discharge and concentration are intimately linked. Concentration data without associated discharge data is unlikely to allow meaningful characterisation of the influent and prevents the load from being estimated. A lack of correlation between discharge and concentration implies that other causal factors may be involved. Failing to collect discharge data will not allow these signals to be spotted and interpreted.

Surrogate data can be used in place of monitoring, but is typically only used:

- Where industry standard approaches have been developed e.g. population equivalents (PE) and other features of the wastewater catchment are used to estimate flow and load discharging into sewage treatment works.
- Where the scenario is sufficiently analogous to another project for which data has been collected i.e. similar by, climate, sizing, treatment objectives, rainfall patterns, catchment etc.

Monitoring at equilibrium

After commissioning, when stasis in biogeochemical performance is reached a Treatment Wetland is at equilibrium. If a sufficiently precautionary design process has been followed, reasonable scientific certainty has been achieved that the design effluent load

/concentration will not be exceeded, and treatment will occur. Equilibrium is therefore the expected operating removal efficacy of the system. In this situation, “compliance monitoring” is not required for nutrient mitigation Treatment Wetlands (Natural England 2022). However, if the Treatment Wetland has a discharge permit limit, then compliance monitoring would be required to satisfy the Environment Agency permit conditions. Regardless of whether monitoring is legally required or not, it is good practice to have a monitoring plan with suitable monitoring frequency, Fig 7.1, to understand performance of the treatment system.

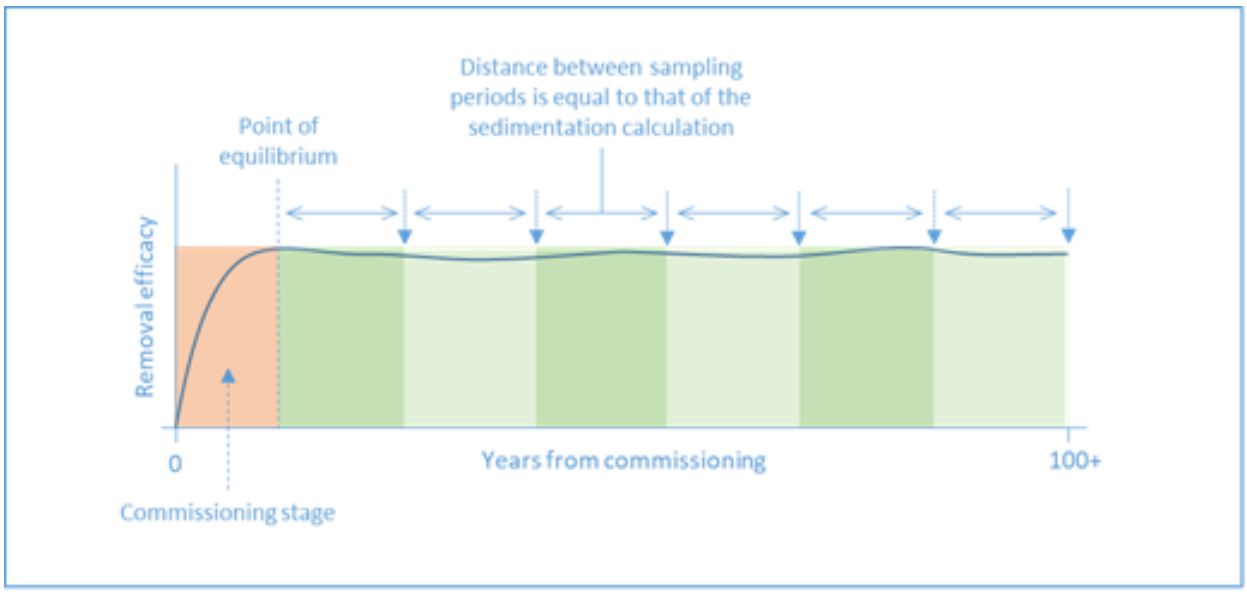


Figure 7.1 A representation of long-term monitoring frequency for a closed-system Treatment Wetland to monitor and evaluate performance.

In many cases the Treatment Wetland will remove more nutrients than was forecast at design, owing to the precautionary approach to uncertainty in the design parameters and variability of inlet waters. If it is a Treatment Wetland for nutrient mitigation measures, additional nutrient credits over and above the ones gained from the initial confidence assessment can be gained through monitoring performance. There is also the potential for non-quantified nutrient removal Treatment Wetlands to be submitted for nutrient credits if monitoring data indicates their reliable performance. The monitoring data would need to be submitted alongside all other required information on design, management and ownership as indicated in the Natural England framework guidance (Natural England 2022).

Monitoring plan – a monitoring plan, that informs management and characterises treatment performance, should be developed considering the following:

- For water quality treatment performance monitoring, the frequency and duration of key pollutant sampling, will be dependent upon the variability of inlet and outlet concentrations and loads so suitable monitoring should be put in place to account for this variability.

- For influent flows that are more event-driven and intermittent, a suitable methodology for monitoring needs to be developed. This can include sampling before, during and after rainfall events or before, during and after peak usage periods in terms of populations or agricultural or industrial production. To achieve this the use of site staff or autosamplers is needed to capture accurate data.
- Tracer tests can be used to establish mean detention time and hydraulic efficiency, particularly identifying preferential flow pathways, which may help to interpret inlet and outlet time series data.
- Water quality sampling can be used in conjunction with visual monitoring to determine performance of the system to inform ongoing management.
- Silt level monitoring is also important to ensure that the wetland continues to function as designed and maintenance is carried out when required. Usually, a maximum silt depth is specified and when this is exceeded silt removal operations are enacted.

Adaptive management

Adaptive management is a useful approach for the long-term management of a Treatment Wetland. It ensures that any changes in terms of water quality and water volume of the influent, which were not predicted at the design stage, can be responded to. Regular monitoring can help inform whether changes in operation and maintenance are required to maintain performance. The management plan should be regularly reviewed and updated if required. Ideally a review of the management plan should take place every year.

Operation and maintenance

Regular visual monitoring of the wetland ensures that it continues to function as designed and the lifespan of blue-green infrastructure is maximised.

Issues arising from blockages, short-circuiting of flow paths, vegetative imbalance and sedimentation can be easily identified using a regular visual assessment and lead to reactive management to rectify the issue before wetland performance is reduced.

Anecdotal evidence shows that nature-based solutions are often not managed optimally in the context of development and therefore do not meet intended targets or objectives due to neglect or improper management. To mitigate this risk, responsible and accountable individuals or bodies should be identified with the responsibility of monitoring and be recorded in the management plan.

Some practitioners recommend regular harvesting of wetland vegetation to enhance nutrient removal (particularly phosphorus removal). This activity will also reduce the rate of sedimentation in the wetlands so may help to reduce some longer term maintenance

activities. Kadlec (2019) argues that the phosphorus content of the harvested vegetation is generally not a particularly high proportion of the overall phosphorus flux in the wetlands, so this activity will only be worthwhile in lightly loaded wetlands. If it is considered, it should always be done in a rotation, to allow refuges for disturbed wildlife, and care must be taken with the method to avoid undue damage to the health of plants, and to avoid large scale disturbance of wetland sediments which could undermine the overall aim. The fate of the nutrient content in harvested plant material also needs to be accounted for in the nutrient balancing calculations.

A commissioning plan stating how long the vegetation should be left to establish before a throughput of water is proposed and when design treatment efficacy can be expected should be developed. The plan should also state how preferential flow paths will be avoided when water is first introduced to the wetland and the assumptions that have been made about treatment efficiency from the immature wetland.

A vegetation management plan stating if regular harvesting of the vegetation is required, what the objective of the harvesting is and what measures are in place to prevent wider damage to the wetland while doing these activities should be developed. The plan should also identify the risk of non-native or ecologically inappropriate species being accidentally introduced and what will be done to mitigate this risk.

Ownership models

Although risk management within the wetland system is controlled through the management plan, external risks, such as land ownership, are more complex to manage.

It is unlikely that the owner of the land, at the time of the design, will own the parcel at the end of the wetland's lifespan so as ownership changes it is important that the management plan and operational information is passed to the new owner and that they are made aware of their responsibilities.

For Treatment Wetlands that are part of a nutrient mitigation credit scheme, it is important that the management plan should include the ownership model relevant to the wetland. There should be some form of guarantee that the treatment benefits from the wetland will not be compromised by any change in ownership. Long term covenants, to secure environmental gains from blue green infrastructure, could potentially be associated with the land and passed to the new owner.

Costings

Introduction & how this section can be used

Cost estimates for each stage of the detailed design of a wetland are highly variable so it is not helpful to estimate actual costs and ranges as part of this report. Instead, this guidance aims to spot the ‘showstoppers’; items within the design process that have the potential to de-rail the project on cost alone. The sooner these issues are spotted the better because this will inform the design process, potentially changing the choice of wetland type and the detailed design itself. We also identify where spending more time and resource early on in the process could save significant costs later on. There are five stages to the detailed design process and the report indicates the percentages of the design budget that should typically be committed to each stage. That said, budget spent early in the design process is rarely wasted because it means that the final design and construction are far less likely to encounter costly issues. For each stage we will report a case study costing to give readers a feel for the costs associated with real projects.

Design Objectives & Feasibility

Agreeing the Design Objectives and conducting a Feasibility study should focus on rapidly removing options that are not viable and highlighting a small number of potential sites and wetland types. Typically, feasibility studies can be expected to account for **5 – 10% of the design budget.**

Case study one: Feasibility study.

This case study relates to six sewage treatment works which may be suitable for the delivery of wetlands. An initial desk-based screening of the sites had already been performed in line with the Feasibility chapter of this report and a template site appraisal had been produced. The cost of this element of the feasibility study is not known.

Additional screening in 2023 based on a site visit by local staff was used to compliment the desk-based study and costed around **£1000** per site. This work included gathering the evidence below:

- Landowner intelligence. Was the landowner known to the local staff and what was their attitude to environmental delivery. Also how engaged are the local community in environmental issues.
- Local multiple benefits based on the accessibility of the site were identified in the desk-based study. The site visit was used to identify evidence that local residents used or could use the area if a wetland was delivered.

- Match funding opportunities based on local knowledge of other environmental delivery in the area.
- Site constraints were identified in the desk-based study however, a site visit can assess the severity of the constraints identified.
- H&S considerations. Similar to constraints above.
- Evidence of environmental impact is useful additional information which could be used to engage the local community and landowner.

Key uncertainties that could be showstoppers at feasibility stage

The following areas of the feasibility study have the potential to escalate the costs of the final project enormously.

Permitting. At the feasibility stage it is highly unlikely that pre-application discussions with regulatory bodies will be helpful, however, it is often possible to use information from a desk-based study or an initial site visit to highlight permits that may be required. Current approval times for permits can be up to 9 months.

- ***Flood risk*** associated with a wetland option in flood zones 2 or 3 mean that a full Flood Risk Assessment (FRA) will be required.
- ***Wildlife or protected habitat.*** If a protected species or its habitat will be impacted, then a wildlife license will be required.
- ***Archaeology.*** If there is a scheduled monument nearby or there is local knowledge of archaeological interest this could increase costs enormously – especially if it is only discovered during the construction phase.
- ***Waste license.*** If the desk-based study has highlighted an historic landfill, contaminated land or mining it is likely that a waste license will be required.

Offsite disposal of spoil due to contamination, flood risk or landowner concerns will always greatly increase construction costs. Even at the feasibility stage options should be assessed to minimise the need for offsite disposal as this can make the difference between an option being viable or not.

Groundwater protection. Lining of the wetland to protect groundwater will significantly increase construction costs and can make the difference between an option being viable or not. The desk-based study can identify groundwater vulnerability and the presence of a Source Protection Zone.

Outline design

Developing the outline design should focus on calculating the treatment area required and integrating this with the landscape and known constraints. 2**0 – 50% of the design budget.**

Case study two: Outline design of polishing wetlands.

This case study relates to the outline design of 5 polishing wetlands downstream of existing sewage treatment works. An initial desk-based screening of the sites had already been performed in line with the Feasibility chapter of this report and key design information on water quality, flow and discharge consents had been provided along with full site investigations and service searches.

The outline design included the initial feasibility screening for this project costed around **£10, 000** per site (2020) with key tasks below:

- A site visit to complement the desk-based study and conduct a more detailed assessment of the potential wetland sites.
- Evaluation of water quality and flow information. For some sites a reasonable timeseries of flow and water quality information was available which allowed the team to estimate ranges for each of the design parameters and therefor minimum and maximum sizes for the treatment area. For other sites estimates the client provided worst case estimates of the input parameters.
- Sizing of the wetland to achieve the required level of treatment and then integrating this treatment area within the landscape based on any constraints identified. This included plan and section drawings for the layout for the sites showing the inlet arrangements, wetland cells and discharge arrangements. The drawings also showed the key water levels to show that the hydraulic design of the wetland did not compromise the function of the existing works, would drive the expected flow through the wetland and discharge to the receiving water course.
- Calculating a water balance to ensure the wetland had sufficient flow in the summer and sedimentation rates to inform maintenance costings.
- Identifying vegetation and commissioning plans.
- Outline cost estimate.
- Ecosystem services benefits assessment.

Key uncertainties that could be showstoppers at outline design stage

Collecting WQ data. The quality of baseline data is critical for claiming nutrient credits. If this data is not available it is likely to add significant baseline monitoring costs and time to this stage of the design. Good data on water quality and flow will reduce the uncertainty and allow wetland size to be minimised, reducing the final construction costs. Low quality data means that a larger wetland will be required to give adequate confidence that the treatment objectives will be met.

Permitting. At the outline design stage it is very productive to have pre-application discussions with regulators and ensure that all the information required for permitting has been collected. The risk appetite of regulators varies across the country – an application

which is straightforward in one area can be extremely problematic in another. Typical ‘showstoppers’ from the Planning and Permitting Chapter are:

- Planning permission. Unless the land is existing agricultural land the wetland will require planning permission.
- Abstraction or Impoundment license. New abstractions or impoundments that may impact a river gauging station are very unlikely to be approved due to the loss of a valuable data source. However, in most catchments the issue should be low risk because wetlands typically only impact a short reach of river between the abstraction and the discharge, making it easy for an abstraction license to be granted.
- Flood Risk Assessment (FRA). Sites within flood zones 2 or 3 can take a great deal of time to get through permitting, especially if pre-application discussions have not taken place. Outline designs which will reduce the storage capacity of the flood plain are unlikely to be granted as are designs which significantly change flood pathways.
- Flood Risk Activities Permit (FRAP) on main river and Ordinary Water Course Land Drainage Consent on ordinary water courses could take time and resources, particularly if the wetland construction is likely to impact bridges or other structures.
- Wildlife license. An ecological survey will be required to establish if the proposed design will disturb wildlife or habitats.
- Environmental permit - Waste license. If contaminated land is present costs for permitting and disposal could be very significant.
- Habitat Regulations Assessment (HRA). If the wetland could impact a protected site then an HRA will be required. For particularly sensitive sites these will be time consuming and expensive.

Offsite disposal of spoil at outline design should be a key consideration, however if topographical data is poor or there is limited site investigation data this cost can be seriously underestimated. Spending more money at this stage to get good quality data will minimise the risk of costs escalating during detailed design or construction.

Groundwater protection. Lining of the wetland to protect groundwater will significantly increase construction costs and can make the difference between an outline design being viable or not. Simple infiltration tests at outline design stage can be used to avoid unnecessary lining costs.

Archaeological features. It is a good investment in time and resources to identify, at the outline design stage, if there is a risk of archaeological features being uncovered at the site. Early engagement with the LA archaeologist could save very significant delay and costs during construction. Additional cost at this stage to save costs later.

Framework consultants vs Independents/third sector. There is a very significant difference between the costs of traditional engineering framework consultants and independent designers/third sector organisations for outline design. Low risk projects can

easily be delivered at significantly lower cost if smaller local organisations are used (so long as they have the required skills). The level of risk associated with the design is the key determining factor as to the type of organisation that should do the design. The CWA now provides accreditation for wetland designers.

Site investigations are critical for identifying the main constraints and if they are not available at the outline design stage a significant amount of money can be wasted at detailed design or during the construction. A basic site investigation is the minimum requirement at the outline design stage.

Engagement with landowner and community. The sooner the landowner and community can be engaged the better. This gives the opportunity to collect key constraints data that can significantly alter the outline design of the wetland and reduce costs at the construction phase. More importantly if landowner and community requirements can be incorporated at outline design it is likely that the scheme will encounter far less resistance and that the final wetland will be an asset to the community. This could significantly reduce maintenance costs.

Identify match funding opportunities. The opportunity to bring in match funding may not reduce costs for the wetland but could ensure that the final design provides a greater treatment area, and therefore improved water quality. Match funding can also increase the value of the multiple benefits delivered by the scheme which has the potential to increase buy-in from the landowner and local community with knock on implications for reducing ongoing maintenance costs.

Detailed design

Developing the detailed design provides the final drawings and specification required by a contractor to cost and then build the wetland. **40 – 75% of the budget.**

Case study three: Detailed design of a polishing wetland.

This case study relates to the detailed design of a wetland to polish secondary treated effluent for a population of 6000. The design costs were **approximately £20,000 (2018)** and the wetland treated a population equivalent of 6000.

Key uncertainties that could be showstoppers at detailed design stage

Most of the key uncertainties that have significant cost implications should have been addressed before detailed design starts. However, there are still some areas of the detailed design that could lead to significant changes in cost.

Offsite disposal of spoil. It is good practice to balance cut and fill within the design to minimise the need for offsite disposal of soil but as the final detailed design develops it is likely that additional complexity will be introduced into the shape and depth of the wetland.

Deeper spreader trenches to ensure suitable water velocities within the wetland have the potential to increase the requirement for offsite disposal although it is unlikely that this will be significant.

Civil engineering. As the detailed design progresses the requirements for civil engineering structures especially at the inlet and outlet will become clearer. These structures can significantly increase the costs of both the design and the construction. Framework consultants are far more likely to revert to these higher cost solutions because they are routinely used in their other designs. Lower cost solutions advocated by small independent designers at the outline design stage can easily be replaced by high-cost alternatives during the detailed design.

Landowner/community willingness. Probably the biggest source of potential cost increase is down to the need to satisfy the landowner or the community if they have not been sufficiently engaged during the earlier stages of the design process. The authors have been involved in projects where landowner concerns over access, maintenance requirements or the aesthetics of a scheme have entailed complete re-designs at the detailed design stage. It is often difficult for non-specialists to engage with outline design drawings and understand the scale and visual impact of the scheme. When this becomes clearer at detailed design stage it can be very difficult to control costs when changes are requested and the goodwill and support of both landowner and community are so important. Early and honest engagement is the best approach.

Construction and commissioning

The construction phase clearly has the greatest potential for cost over runs. The actual costs of construction can vary enormously based on the scale and location of the wetland. This section will focus on the key aspects of this phase that could impact the final construction phase of the project.

Case study four: Construction of a number of FWS polishing wetlands

> **£225,000 (2018) for a wetland treating** 6000 PE with a treatment area of 1 hectare and a site area of 3 hectares.
> **£270,000 (2023)** 1000 PE.
> **£40,000 (2019)** small rural treatment works.
> **£3,000,000 (2024)** similar size to the first two examples and shows the variability in costs.

The variability of the costs above show how important it will be to collect this data over time to give a much fuller picture of actual costs and the key factors that influence them.

Key uncertainties that could increase construction costs

The following issues all have the capacity to significantly increase costs. The risk will have been minimised by investing more in the earlier stage of the project but they cannot be eliminated. Once a contractor is on site any delays to the construction program are likely to become a compensation event. Hire costs of any plant and equipment plus the day rate of construction staff who cannot proceed with the work are all legitimate additional costs that will be added to the overall construction cost.

Land costs for lease or purchase. These costs can have an enormous impact on the total budget. Experience suggests that building a good relationship with the landowner with an ‘honest broker’ is most likely to lead to reasonable and fair valuations.

Issues with landowner. It is critical to have a landowner agreement before work on site commences. This should set out the boundaries of the site; access to and from the site; the location of cabins and welfare facilities; the location of storage both for construction material and temporary spoil heaps. If a landowner changes any of the details set out in the original tender documents the contractor may need to submit a compensation event.

Delays due to permits and planning. This clearly increases the risk that work will have to be paused if they are not in place by the time required in the construction program.

Uncovering archaeology. Early engagement with the county archaeologist has been suggested in the design stages above. However, there is always the risk that archaeological features will be discovered during the construction. The delays to work and potential need for re-design to avoid or protect features has the capacity to seriously increase construction costs. It is not possible to remove this risk entirely.

Unexpected ground conditions. Exposing a groundwater input or encountering unstable soils e.g. running sands, may require both a delay to the project and a redesign of the wetland. The risk can be minimised by site investigation at the earlier design stages but cannot be removed.

Hydrological commissioning. There should be a commissioning plan which shows how the contractor will check the hydraulic integrity of the base of the wetland and any pipework. If issues are identified these would typically fall on the contractor to rectify and should not increase costs. A commissioning plan for polishing wetlands also requires coordination with the owner of a treatment works and the operation of the works may dictate when commissioning can take place.

Vegetation establishment – There should be a planting plan which allows for some plant loss due to disease etc and the protection of the plants from birds and animals. It is likely that this plan will also seek to establish plants at an optimum time of the year to minimise

the need for replanting. However, construction delays or unseasonal weather can both have a serious impact on plant establishment and survival.

Framework contractor vs local contractor. Local contractors are likely to cost less than framework contractors, partly because they have lower mobilisation costs, but also because they are part of the local economy and therefor rely on repeat business within the area. Many local delivery organisations build strong relationships with their contractors which means that they tend to be more flexible if delays occur and develop specialisms in the unique elements of wetland construction. This also helps to reduce costs.

Maintenance, Adaptation and monitoring

Example costs for the maintenance and monitoring phase is the least well-known element of the costing. This section will focus on the key aspects of this phase that could impact the long-term costs of the project.

Case study five: Maintenance and monitoring of a 1 hectare treatment wetland within a 3 hectare site (2018). The agreement covers the management of trees and grass within the site and the monitoring of the wetland itself and the wetland plants. Key factors that affect costs include distance to the wetland and number of visits (neither are known for the case study below):

- £4,000 per annum paid as a one-off upfront payment for 20 year period. Experience has suggested that the actual costs of maintenance are significantly higher with £8,000 per annum a more realistic estimate.
- Lease cost of £5,000 per annum as a single upfront payment for 20 year period for a 3 hectare site.
- It will be important to collect this data over time to give a much fuller picture of actual costs and the key factors that influence costs.

Key uncertainties that could increase costs

There is limited data on the actual cost of maintenance and adaptation. , Most of the tasks that will be required to retain a wetlands ability to remove nutrients are well understood and can be included in a realistically costed maintenance plan. However, the future frequency of these tasks in the light of climate change is less well understood. This is particularly important if delivery organisations are to sign up to long term management contracts based on one off, upfront payments.

The Delivery organisation. It is likely that a local organisation or even a community group will be far less expensive than a commercial company. However, maintenance and adaptation is a long-term endeavour for these wetlands, if nutrient removal is to be maintained. It is therefore important that the organisation responsible for this task is likely

to have a long-term future and be committed to the retention of both the nutrient reduction and wider multiple benefits of the wetland.

Sediment removal. Climate change predictions identify that high intensity storms will become more frequent in the future. This means that the mobilisation of sediment from the soil is likely to increase and that the frequency of sediment removal will also increase. The importance of designing easy maintenance into the wetland layout, detailed design chapter , is clearly critical if these costs are to be minimised.

Re-planting. As the climate changes, patterns of disease and changes to the water balance may increase the frequency of re-planting. This is partially covered in the detailed design chapter.

Adaptation. As the nutrient load or flow into the wetland changes it may need to be adapted or enlarged if its nutrient removal capacity is to be retained. Landuse change and increasing population will require this adaptation and this needs to be factored into the maintenance plan and maintenance payments. This approach is possible and is being implemented within a number of innovative green finance approaches for nature based solutions. The funding model includes a budget for adaptive management. This allows the intervention to be delivered based on current design assumptions but continue to deliver in the future if the assumptions are proved incorrect.

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Additional material on weirs

Following first principles, the total flow through the system when the water level is at the top of the dam will be the flow through the v-notch, plus the permeate flow through the dam. As the channel flow increases, the water level rises until flow surcharges the dam, and eventually surcharges the v-notch weir where the exceedance flow is directed to the wetland via the spillway.

To summarise, the total flow for any water level in the stream channel (upstream of the dam) is calculated as follows;

The total flow $Q = Q_1 + Q_2 + Q_3 + Q_4$

Where:

***Q_3 = Flow to the stream (calculated as orifice flow, permeating the dam)**. Using the principle of orifice flow (discharge through a small opening, driven by the hydraulic head, h, upstream) it can be assumed that the permeate flow is produced from the sum of all orifices (gaps) between the structural components of the dam over the submerged cross-sectional area of the dam. The calculation of permeate flow, Q_p, through the dam is as follows:*

$Q_p = C_d A_o \sqrt{2gh}$ *(from Chadwick, Morfett & Borthwick, 2004)*

$C_d = C_v C_c = 0.622$ *(from Chadwick, Morfett & Borthwick, 2004)*

A_o *= Sum of 'gap' areas = Submerged area of dam x porosity =* $A\varphi$

h = the average upstream head diving the permeate flow (m), assuming that the gaps are distributed equally over the height of the dam

The design porosity φ *of the dam should be ~1% to ensure sufficient head is retained upstream. This will require the dam to be constructed from uniform materials that fit together without creating so many gaps, such as timber railway sleepers stacked flatways.*

***Q_2 = Flow into the wetland (through the v-notch weir)**. The advantage of the v-notch is that it is more accurate for the low flows (when h is 75mm or lower), unlike a rectangular weir. Monitoring of the head over the weir will therefore provide an accurate flow measurement, if flow monitoring is required. The formula below is from Chadwick, Morfett & Borthwick, 2004.*

THIN PLATE (SHARP CRESTED) V-NOTCH WEIR

$Q = C_d\, 8/15\, \sqrt{2g}\, \tan(\Theta/2)\, H^{5/2}$

$Q = C_d\, 2.35\, H^{2.5}$

Q = discharge flow in m^3/s

$\Theta = 90°$

H = height above notch invert (m)

C_d = Coefficient of discharge, 0.59

Figure: V-Notch weir calculation

Q_1 = Additional flow to the stream (calculated as weir flow, surcharging the dam) *For the higher channel flows, the water will overtop the dam and it will behave as a weir. The flow over the weir can be calculated using the Rehbock formula, which is applicable for uncontracted weirs that are the full width of the channel:*

$$Q = \frac{2}{3}\sqrt{2g}\left(0.602 + 0.083\frac{h}{Ps}\right) b(h + 0.0012)^{\frac{3}{2}}$$

(from Chadwick, Morfett & Borthwick, 2004)

Ps = height of dam above stream bed (m)

h = upstream head above dam (m)

Q_4 = Additional flow to the wetland (calculated as weir flow, surcharging the sidewall spillway). *As the channel flows increase >Q50, the v-notch weir will eventually become drowned (v-notch at full capacity) and a greater amount of flow is directed into the wetland as it passes over the sidewall spillway. At this point, the permeate flow through the dam is no longer considered as it is conservative to assume that the dam is blocked (for the purposes of flood risk assessment). The cross-sectional area of the spillway above the sidewall is greater than that of the dam, so that the loss of channel capacity is over-compensated.*

Once breached, the sidewall / spillway behaves like a broad crested weir. At this point, flow from the channel is discharged as flow over the v-notch (at full capacity), additional flow over the sidewall / spillway and flow over the dam.

Flow over broad crested weir:

$Q = C_d\, 1.705\, b\, H^{1.5}$ (from Chadwick, Morfett & Borthwick, 2004)

H = height of water level above the sidewall

b = breadth of weir, which is the width of the sidewall (m)

C_d = 0.8

Each of the above flows will have a different value of h to be used in their calculation. This is illustrated in the diagram below.

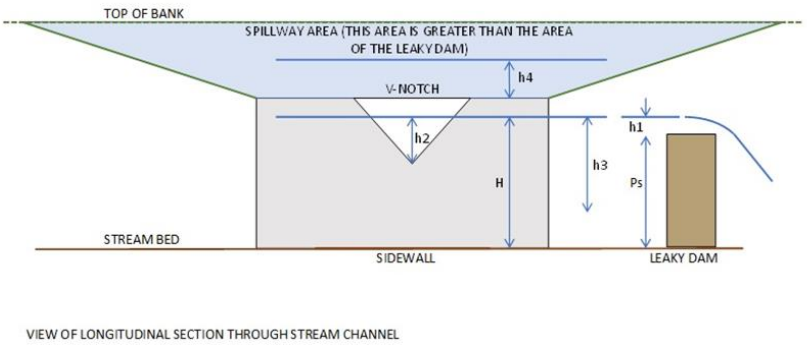

Figure. Various values of h for different flow calculations

Q_3 calc uses h3, where h3 = (H + h1) / 2

Q_2 calc uses h2

Q_1 calc uses h1

Q_4 calc uses h4 (assuming that the sidewall / v-notch channel is a broad crested weir)

It is normal practise to create a table of h vs Q, for given inputs of h, increasing incrementally.

The typical daily flow through the wetland will be that which is diverted from the stream channel at the Q50 flow (the median flow rate). This can be determined by creating a table of calculated flows for a range of water levels in the stream channel, and then cross referencing the total flow, Q with the modelled catchment flows so that the likely stream depth and flow distribution can be seen for the Q50 flow. The Q95 flow can also be checked, to see if a flow is diverted to the wetland at least 95% of the time. The following tables are an example of a stream channel with a total depth of 0.8m, and a catchment area of 10.99 km^2 . The first table shows the lower range of flows up to Q50, and the second shows the higher range of flows up to the Q5. As described earlier, the Q_3 flow (permeate through the leaky dam) is ignored for the higher range, as it is assumed to be blocked.

Water level above stream bed, H	Height above dam, h1	Height above v-notch, h2	Average head behind dam, h3	Q_3 m³/s	Q_2 m³/s	Q_1 m³/s	**Q m³/s**
0.000	0.000	0.000	0.000	0.000	0.000	0.000	**0.000**
0.100	0.000	0.000	0.050	0.005	0.000	0.000	**0.005**
0.200	0.000	0.000	0.100	0.007	0.000	0.000	**0.007**
0.300	0.000	0.000	0.150	0.009	0.000	0.000	**0.009**
0.400	0.000	0.100	0.200	0.010	0.004	0.000	**0.014**
0.450	0.050	0.150	0.250	0.011	0.012	0.004	**0.028**
0.475	0.075	0.175	0.275	0.012	0.018	0.012	**0.042**
0.500	0.100	0.200	0.300	0.012	0.025	0.024	**0.062**
0.525	0.125	0.225	0.325	0.013	0.033	0.043	**0.089**
0.550	0.150	0.250	0.350	0.013	0.043	0.067	**0.124**

Q95 = 0.034

Q50 = 0.095

Water level above stream bed, H	Height above dam, h1	Height above side-wall, h4	Q_2 m³/s	Q_1 m³/s	Q_4 m³/s	**Q m³/s**
0.575	0.175	0.025	0.043	0.098	0.011	**0.152**
0.600	0.200	0.050	0.043	0.137	0.030	**0.210**
0.625	0.225	0.075	0.043	0.184	0.055	**0.282**
0.650	0.250	0.100	0.043	0.239	0.084	**0.366**
0.675	0.275	0.125	0.043	0.303	0.118	**0.464**
0.700	0.300	0.150	0.043	0.376	0.155	**0.574**
0.725	0.325	0.175	0.043	0.459	0.195	**0.697**
0.750	0.350	0.200	0.043	0.553	0.238	**0.834**
0.775	0.375	0.225	0.043	0.656	0.284	**0.984**
0.800m	ASSUME STREAM BANK BREACHED AND IN FLOOD					

Q10 = 0.296

Q5 = 0.410

Figure 5.9. Table of calculated flows for various depths within a channel of known dimensions. Percentile flows (Q95, Q50 etc) from the contributing catchment can be 'mapped' onto the table to see which water levels they correspond with.

Glossary

Term	Description
Wetland	"*Wetlands are land areas that are wet during part of all of the year because of their location in the landscape*" [1] They are usually characterised by the presence of water, either at the surface or in the root zone; possess unique soils different form adjacent 'uplands'; and support vegetation adapted to wet conditions.[2]
Constructed Wetland/ Treatment Wetland/Wetland treatment system	A constructed or treatment wetland is an "*engineered systems designed to optimise processes found in natural environments and are therefore considered environmentally friendly and sustainable options for water treatment*" [3] Wastewater is treated through a complex range of processes which occur within the wetland which include sedimentation, uptake of nutrients by plants and reduction of pathogens through exposure to UV. Constructed Wetlands range from simple vegetated pond-based systems up to complex, multi-stage systems treating concentrated point-source effluent.
Free water surface (FWS) wetlands	"*Resemble natural wetlands in appearance.* *Require large surface area, are generally lightly loaded.* *Various plant genus can be used…* *…Are mainly used for tertiary treatment*." [3]
Horizonal subsurface flow (HSSF)	"*Wastewater flows horizontally through a sand or gravel based filter whereby the water level is kept below the surface.* *Due to the water-saturated condition mainly anaerobic degradation processes occur.* *Effective primary treatment is required to remove particulate matter to prevent clogging of the filter.* *Emergent plants (macrophytes) are used.* *Are used for secondary or tertiary treatment*". [3]
Vertical flow (VF)	"*Wastewater is intermittently loaded on the surface of the filter and percolates vertically through the filter.* *Between two loadings air re-enters the pores and aerates the filter so that mainly aerobic degradation processes occur.* *Effective primary treatment is required to remove particulate matter to prevent clogging of the filter.* *Emergent macrophytes are used".* [3]
Reedbed	A reedbed (in the context of water treatment) is one of many types of constructed wetland. It is a type of simple horizontal sub-surface flow wetland in which the plant species composition is dominated by Common reed *Phragmites australis*.
Integrated Constructed Wetland	An Integrated Constructed Wetland (ICW) is a large biodiverse free water surface wetlands that fits in with the surrounding lanscapes. They are typically found in rural areas and are unlined.
Influent	(Waste) water entering a system (such as a wetland)
Effluent	(Waste) water leaving a discharge point (such as a sewage treatment works) and entering a (wetland) system

Concentration	The mass of a parameter in a defined volume of water (for example, milligrams of total phosphorus per litre (mgTP/l or $mgTPl^{-1}$) or PPM)
Load	The amount (mass) of a parameter that is discharged into a water body over a set period of time (for example, kilograms of total nitrogen per year (kgTN/yr or $kgTNyr^{-1}$))
HLR	Hydraulic loading rate - rate at which water is discharged to a wetland treatment system, expressed in volume per unit area per unit time or depth of water per unit area per unit
HRT	Hydraulic Retention Time – the average time taken for water to pass through a wetland. The HRT is calculated by dividing the volume by the flow (usually in days)

[1] Kadlec, R. H., & Wallace, S. (2008). Treatment wetlands. CRC press.
[2] Mitsch, W. J., & Gosselink, J. G. (2015). *Wetlands*. John Wiley & Sons.
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Additional terms used in the design guide

C*	Background concentration of a parameter found in wetlands below which further reduction in concentration is not possible
g	Gram
k	Reaction rate constant used in design equations
Kg	Kilogram
ha	Hectare
L or L	Litre
m	Metre
mg	Milligram
N	Chemical symbol for nitrogen
P	Chemical symbol for phosphorus
pe	Population Equivalent – the average amount of water, or another component, produced by one person during one day
PPM	Parts per million
SS	Suspended solids – usually defined as the concentration of particulate material in a volume of water
TN	Total nitrogen
TP	Total phosphorus.
yr	Year
Karstic	Limestone or similar fractured rock geology. Groundwater pollution can travel rapidly through these systems and pollute drinking water abstractions.