CRC for Contamination Assessment and Remediation of the Environment

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no. 5

technical report

The development of a modular, constructed wetland system for salt, organic and nutrients removal from dairy wastewaters

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Agriculture Victoria Services Pty Ltd

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Executive summary

This is the final report of a desk-top study designed to provide 'proof-of-concept' for the use of the giant reed (*Arundo donax*) in constructed wetland systems designed to remove contaminants from dairy processing factory wastewater streams. Activities were therefore restricted to information collection, collation and evaluation. No field or laboratory activities were planned or have been conducted. The following conclusions and recommendations can be made with respect to the objectives of the project.

The giant reed is a perennial, herbaceous plant found in grasslands and wetlands over a wide range of climatic and habitat conditions. The giant reed is found in most parts of Australia, including in Victoria, but is not listed as a noxious or invasive weed Australia-wide, although it is locally declared in New South Wales (and thus its use is also prohibited in Western Australia). The giant reed is not a declared weed in Victoria, and is apparently readily available from a number of garden suppliers. However, *A. donax* has some traits, such as fast growth rate, diffusion via flood-mediated rhizome dispersion, rapid re-growth after fire, and invasion of riparian zones that make it a potential weed. Before *A. donax* is used in constructed wetlands in Victoria, South Australia, Queensland, the ACT, Northern Territory or Tasmania, consideration should be given to a detailed survey of its distribution within the relevant state. Such a survey should include an ecological assessment of local and/or regional adaphic and biotic factors that may constrain or promote its ability to become a weed.

Arundo donax has some characteristics that make it suitable for use in constructed wetlands for wastewater treatment. These include its fast growth rate, high water consumption, apparent salt tolerance (still to be confirmed), ease of propagation from rhizomes, limited reproduction from seed (reduced risk of off-site dispersal), limited number of pests, and the many potential uses for above-ground biomass. There is limited information on the use of *A. donax* in constructed wetlands, although the giant reed has been planted in several research and treatment wetlands (e.g. in Arizona and Crete). Very little treatment performance data is available for these wetlands, although the tendency for impenetrable stands of *A. donax* to rapidly dominate reed-bed systems has been noted.

Constructed wetlands are currently not able to remove sodium originating in factories and associated anaerobic water treatment plants. However, finding plants able to tolerate high salt loads could facilitate the use of constructed wetlands to ameliorate the organic and nutrient loads being discharged by factories. Insufficient detailed information on *A. donax* exists to adequately assess the advantages and limitations of *A. donax* compared with other common wetland plants (e.g. *Phragmites australis)*. Consideration should be given to the establishment of pilot scale wetlands using *A. donax* to:

- examine the effectiveness of the giant reed (*A. donax*) in stripping nutrients and organic material from effluent by evaluating chemical transport, assimilation and release in pilot scale constructed wetlands, and in comparison with the common reed (*Phragmites australis*)
- assess the salt tolerance of *A. donax*
- examine options for the sustainable re-use of the biomass produced by *A. donax*
- investigate management techniques to minimise risk of escape of *A. donax* from constructed wetlands.

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Glossary of terms

BOD_5: Biochemical (biological) Oxygen Demand. Substance concentration of oxygen taken up through respiratory activity of micro-organisms growing on organic compounds present when incubated at a specific temperature (usually 20^{o}C) for a fixed period (usually five days). BOD is regarded as a measure of that organic pollution of water which can be degraded biologically, but includes the oxidation of inorganic material such as sulfide and iron (II). The empirical test used in a laboratory to determine BOD also measures the oxygen used to oxidise reduced forms of nitrogen unless their oxidation is prevented by use of an inhibitor (such as allyl thiourea) (IUPAC 1993).

Bog: Acidic wetland dominated by mosses which accumulate peat. Can be forested.

Bottomland: Floodplain wetlands typically dominated by wetland tree species.

COD: Chemical Oxygen Demand. Substance concentration of available oxygen (derived from a chemical oxidising agent) required to oxidise the organic (and inorganic) matter in wastewater (IUPAC 1993).

Concentration: The quantifiable amount of a substance in water, food or sediment.

Contaminant: A substance that is present in the environment. A material described as a 'contaminant' is one that is either not naturally present in the environment or is present in unnatural concentrations, but in being described as such, no judgement about whether or not the material is having an adverse effect on the environment, or organisms therein is being made – the material is simply present in the environment.

Constructed wetlands: Purpose-built structures, utilising the predominantly natural materials of soil, water and biota, which perform the desired physical, chemical and biological processes and functions of natural wetlands to achieve desired objectives.

- The term 'constructed wetland' includes not just the wetland, but all associated elements, e.g. gross pollutant traps, sedimentation ponds, macrophyte beds, littoral zone, open water areas, islands, weirs, flow control (Kadlec & Knight 1998).

Fen: Wetland occurring on low, poorly drained ground and dominated by herbaceous and shrubby vegetation. Soil typically peat or marl.

Guideline: Numerical concentration limit or narrative statement to support and maintain designated water use.

Macrophyte: A plant which is large enough to be seen without a microscope.

Marsh: Wetland dominated by emergent soft-tissue macrophytes (e.g. cattails, reeds, bulrushes).

Metal: Any element in Groups Ia, IIa, IIIb, IVb, Vb, VIb, VIIb, VIIIb, Ib, IIb, IIIa, and rows 4–6 of Groups IVa, Va and VIa of the Periodic Table. For the purpose of this report, the term 'metal' includes the metalloid arsenic (As), and covers those elements normally termed 'heavy metals' (metals with atomic numbers between 21 (Sc) and 92 (U)).

Natural wetlands: Transitional areas between deep, open water and dry land. Natural wetlands:

- include areas of land which are cyclically, intermittently or permanently inundated or saturated with fresh, brackish or saline water
- show an array of biota (fauna and flora) dependent on inundation.

Plug flow: The concentration of the reactant decreases along the length of the flow path through the reactor compared with a completely mixed reactor where the concentration of the reactant is the same at any point in the reactor.

Toxicant: A chemical that can produce adverse health effects.

Total Suspended Solids (TSS): A measure of the suspended solids (non-dissolved material) in wastewater, effluent, or water bodies, determined by tests for 'total suspended non-filterable solids'.

Sediment: Unconsolidated mineral and organic particulate material that has settled to the bottom of aquatic environments.

Wet prairie: Shallow wetland dominated by sedge and grass species.

Wetland: A relatively new way to describe landscapes many people know under different names (e.g. fen, bog, bottomland, marsh, swamp, wet prairie). However, although land and water can merge in numerous ways, three main factors characterise wetlands:

- sustained or repeated saturation of the soil with water (e.g. seasonal inundation or recurrent irrigation)
- soil physical and chemical properties that result from soil saturation (e.g. hydric soils)
- the presence of biological organisms adapted to the saturated conditions.

Thus wetlands include a wide range of ecosystems. At their upslope margin, wetlands can be distinguished from uplands by the latter's tendency to remain flooded or saturated for short enough periods that oxygen and other soil conditions do not limit plant growth (less than 7–30 days per year). At their downgradient edge, wetlands grade into permanently flooded systems where emergent, rooted plants cannot survive (typically 1–2 m in depth).

1. Introduction

The food processing industry generates high organic wastes and/or high levels of salts in their wastewater. Pressure to reduce discharges to meet regulatory requirements is driving the search by industry for newer, better and more cost-effective ways to treat the wastewater. There is a need for modular technologies that will not only treat the organic loading and nutrient content of wastewaters generated by the industry, but also simultaneously remove the salts originating in factories and associated anaerobic water treatment plants.

This is a desk-top project designed to provide 'proof-of-concept' for the use of an alternate, multipurpose species of macrophyte (*A. donax*) in constructed wetland systems designed to remove nutrients from wastewater streams.

1.1 Background

The Department of Primary Industries (Victoria)'s strategic research and development plan for CRC CARE is framed on solid and liquid organic wastes. The work program is modular, and is focused on strategically located flagship research sites in rural and regional Victoria. Four flagship sites currently exist including a composting facility at Werribee, a dairy demonstration farm located in south-west Victoria, an irrigation field site located in the Goulburn Valley, and a viticulture site located at Mildura. These key sites take an industry-based approach towards the development of viable options for key agricultural industry waste issues.

In all parts of the food and beverage industry concerns are voiced about difficulties in dealing with high organic wastes and/or high levels of salts in their wastewater, and the pressures to reduce discharges to streams, waterways and the environment. The dairy industry is no exception. Pressure to reduce discharges to meet regulatory requirements is driving the search by industry for newer, better and more cost-effective ways to treat the wastewater. Equally important is the need to increase recycling and re-use of water primarily to reduce costs associated with buying treated water as much as higher goals of securing the water resource into the future. Nutrients, organic load (as measured by BOD or COD), suspended solids and dissolved salts (particularly sodium (Na)) are the major constituents of concern.

Constructed treatment wetlands are able to treat the organic loading and nutrient content of the wastewaters generated by the food and beverage industry to levels appropriate for land application. For instance, work conducted by Allinson et al. (2005) on the constructed wetlands at Masterfoods' Ballarat site highlighted how the proper functioning of a constructed wetland for water treatment relies on the interaction of three components: water quality, wetland design, and the wetland plants. Our evaluation of the Masterfoods wetlands suggested that there was nothing wrong with the design, nor the original planting regime, and that the system should reduce BOD and suspended solids to desired levels. However, water quality, and in particular salinity, exceeded many of the original design parameters, causing improper functioning and requiring a complete renovation of the system.

Constructed wetlands are currently not able to remove sodium originating in factories and associated anaerobic water treatment plants. Until a Na hyper-accumulating floating or emergent macrophyte is found or developed, other alternatives are required. One option – to use a plant that can live in the effluent discharged by the food and beverage industry – may provide a cheap, ecological alternative to treating saline effluents compared with membrane-based hard engineering options, and could be incorporated into existing treatment wetlands as well as new wetlands. This project will assess the giant reed (*A. donax*) for use in constructed wetlands designed to treat high-BOD, high salt wastewaters.

1.2 Objectives

This project aims to further significantly increase the resource use efficiency of Victoria's farming and food production industries and create opportunities for liquid wastes to be recycled in manufacturing or production systems.

The project will build on effective industry partnerships developed by DPI and principal investigator Dr Graeme Allinson over the past few years to leverage industry funding of government outcomes in waste reduction and recycling. These include the Dairy Industry Sustainability Consortium – Closing the Loop project managed by Dr Allinson. Closing the Loop is an 'holistic approach to the management of dairy processing waste streams' that aims to provide the Victorian dairy industry with tools to reduce the $28 million spent each year on waste management. The CTL project focuses on alternative technologies and methods to reduce salt and biosolid loadings in wastewaters, recovery of solid organic wastes, and the development of best practice guidelines for land application of wastes to minimise environmental risk.

This initiative will focus on high value production landscapes (the dairy sector) to reduce waste and increase resource use efficiency. The following outcome is sought:

- New systems and processes to reduce salt and nutrient levels in dairy factory wastewaters using constructed wetlands.

The objectives of the project are to:

1. Critically review existing information/studies related to the use of *A. donax* in industrial wastewaters, and any political/legal restrictions there might be to their use in Victoria.
2. Investigate the potential use of *A. donax* to treat dairy factory wastewater streams.
3. Design modular systems for the removal of Na salt from dairy factory wastewaters (including chemical, analytical and biomonitoring techniques).
4. Develop linkages and seek co-funding for the construction/validation phase of the project from potential co-investors.

2. Constructed wetlands for water treatment

Natural wetlands have been used for centuries, by many different communities and cultures, and in many different countries for waste disposal. However, the self-purification services offered by natural wetlands have extremely variable functional components, making it difficult to predict responses to wastewater application from one wetland and region to another. Engineered wetlands, or constructed wetlands, are artificial systems constructed to take advantage of many of the same processes that occur in natural wetlands, but in a more controlled environment. Constructed treatment wetlands thus use natural processes involving wetland vegetation, soil and associated bacterial, fungal and other microbes to assist in treating wastewater. The number of constructed treatment wetlands increases every year, and if designed and used properly offer opportunities in many areas to regain some of the natural ecosystem services and functions lost when natural wetlands were drained or filled for agricultural and other purposes (Kangas 2003).

The use of constructed wetlands for the treatment of industrial, municipal and stormwater flows is becoming popular in Australia. In many instances, their use in water quality treatment is considered to be 'environmentally friendly', and preferred over more traditionally engineered, higher energy intensive technologies. In some cases, where wetlands are constructed to enhance degraded habitat, there is no other alternative to these ecologically engineered environments (DLWC 1998).

The planning, design, construction and operation of a constructed wetland involves activities in a number of different disciplines, including chemistry, hydrology, soil science, plant biology and environmental management. Because no one individual ever has all these skills, wetlands are best constructed using a team approach involving members with inter-disciplinary skills. Without such an approach, too many wetlands have been developed that are inappropriate, under-performing or otherwise failing to achieve the design's potential (DLWC 1998). The reasons for these problems include:

- **The perception that constructed wetlands are 'magical,' with the ability to cure all evils**. For instance, constructed wetlands have been used to treat urban stormwater, municipal, industrial process, mine site and agricultural wastewater. They have been used to provide habitat, recreational and visual amenity, research and educational sites, modify water flow and provide economic returns. However, anecdotal evidence suggests that once built many, if not most, wetlands are not monitored or adequately maintained, and that many wetlands fall well short of expectations.
- **Lack of appreciation by designers and operators of complex physical, ecological, and chemical processes within constructed wetlands**. They may be simple in engineering terms, but constructed wetlands are extremely complex ecological systems. The success of many projects depends on understanding the complex inter-play between hydrology, botany, ecology, limnology, and soil and water engineering – not a design philosophy based on 'transposed digits' (crossed fingers!).

- **Lack of consistency in design, construction and operation aimed at optimal performance.** Constructed wetland designers and builders come from a number of different backgrounds, including civil or chemical engineering, ecology, landscape architecture, microbiology, soil science and natural resource management. Each discipline has its own philosophies, which suggest what must be done first, what important questions must be addressed and who should address them. Ultimately, designers with different backgrounds and philosophies can end up producing different designs for the same site. This is only a problem if the designer favours only a single outcome, whether it is social, technical or environmental, over a more balanced outcome. Similarly, ecological complexity and the full range of issues and impacts in constructed wetlands may not be covered.
- **Lack of appropriate design tools and methodologies for local conditions.** Many of the design tools for constructed wetlands have been designed in Europe or North America, and may not be appropriate for Australian conditions. Consequently, Australian biota has different requirements to that of the biota studied in other countries, and their response to inundation will be different. In Australia, phosphorous is a key limiting nutrient in many waters, and so is a key concern, whereas in many parts of the Northern Hemisphere nitrogen takes precedence. If design tools imported from overseas should be used cautiously, then so, indeed, should design tools and strategies developed in other parts of Australia. A design developed in one state or territory in Australia may not be applicable in the other states or territories. For instance, the hydrology and climate in northern New South Wales is different to that of southern Victoria, Adelaide, and Western Australia, and so the species used in the design must change accordingly.
- **The changing nature of a rapidly developing and maturing technology.**

(DLWC 1998)

One question that must be asked when considering constructed wetlands for wastewater treatment is ‘when is it appropriate technology?’ The answer is, ‘it depends’, and not least on the quality and toxicity of the water to be treated.

Domestic wastewater is arguably the least toxic wastewater produced by humans, and it is therefore not too surprising that ecologists would choose it as the first to treat in wetlands. The dominant parameters of sewage that require treatment are:

- organic materials (as measured by BOD)
- total suspended solids (TSS)
- nutrients (primarily nitrogen and phosphorus compounds)
- pathogens (microbes including viruses and faecal coliform bacteria).

Wetlands can be said to be ‘pre-adapted’ to treating these parameters since they act as a ‘sponge’ in absorbing and slowly releasing water flow, and as a ‘filter’ in removing materials from the water. Wetlands can provide primary or secondary treatment of municipal wastewater, however they are more usually used for ‘polishing’ of the water beyond secondary treatment.

Industrial and mining related wastewater is arguably the most toxic wastewater produced by humans, and it is therefore not too surprising that only a fraction of industrial facilities' discharges are suitable for amendment by wetlands. Many industrial discharges contain potentially toxic chemicals at concentrations that could be detrimental to the wildlife within, or attracted to, wetland systems. Pre-treatment of industrial wastewaters is the norm, before the natural processes found in treatment wetlands can be used. The dominant parameters of industrial effluents that require pre-treatment are:

- organic materials (BOD, COD, TSS, TN, colour)
- salts
- nutrients (primarily nitrogen and phosphorus compounds)
- grease
- trace metals.

Constructed wetlands

Constructed wetland systems are engineered wastewater treatment systems. Unfortunately, a few of the wetland descriptions have been used synonymously and need precise definition to ensure common understanding.

- **Restored wetlands:** Areas that previously supported a natural wetland ecosystem but, having been modified and used for other purposes, have been altered to return to poorly drained soils and wetlands flora and fauna.
- **Created wetlands:** Former well-drained soils supporting terrestrial flora and fauna that have been deliberately modified to establish poorly drained soils and wetlands flora and fauna.
- **Constructed wetlands:** Former terrestrial environments that have been modified to create poorly drained soils and wetlands flora and fauna.

Constructed wetlands for wastewater treatment can be further classified according to the life form of the dominant plants, and the way water flows through the system.

System	Dominant life-form
Free-floating macrophyte based systems	Large plants with rosettes of aerial and/or floating leaves, e.g: • *Eichornia crassipes* (water hyacinth) • *Pistia stratiotes* (water lettuce) • *Hydrocotyle umbellata* (pennywort) to Small floating plants with few or no roots (duckweeds), e.g: • *Lemna spp*. • *Spirodela polyrhiza* • *Azolla spp*. • *Wolffia spp.*
Submerged macrophyte systems	Plants have photosynthetic tissue entirely submerged: • *Egeria densa* (dense waterweed, Egeria, Brazilian Elodea) • *Elodea canadensis* and *E. nuttallii* (waterweeds) • *Ceratophyllium demersum* (coontail, hornwort) • *Hydrilla verticillata* (hydrilla) • *Cabomba caroliniana* (fanwort) • *Myriophyllium heterophyllium* (water milfoil) • *Potamogeton spp.* (pondweeds)
Rooted emergent macrophyte based systems	Plants produce aerial stems and leaves and have extensive root and rhizome systems. Plants are morphologically adapted to growing in water logged or submersed substrate: • *Scirpus spp*. (bulrushes) • *Phragmites australis* (common reed) • *Glyceria spp*. (mannagrasses) • *Typha spp*. (cattails) • *Zizania aquatica* (wild rice)

Treatment wetlands can be said to be an adaptation of *upland natural treatment systems*. On-site infiltration, land application, and overland flow systems all rely on the use of relatively well drained land for treatment. All use an unsaturated soil layer to provide either direct filtration and assimilation of pollutants, or a rooting/growth medium for terrestrial plants which filter solids and absorb pollutants from the wastewater.

- **On-site systems** provide treatment with a discharge to groundwater, and include household and community septic tanks and their drain fields.
- **Slow-rate land application systems** use irrigation of vegetated systems for wastewater polishing and disposal. Irrigation rates are low and intermittent, allowing the soil to re-establish aerobic conditions periodically. The aerobic conditions are required for the terrestrial plants to thrive, and these in turn are essential for nutrient removal, solids filtration and maintenance of soil texture.
- **High-rate land application systems** use highly permeable soils for groundwater discharge. Groundwater mounding occurs below the infiltration basins, so often multiple basins and basin rotation are used to allow dry down and resting between inundations.
- **Overland flow systems** rely on the intermittent application of wastewater to the top of sloped, vegetated terraces, after which the wastewater flows by gravity down the slopes to collection channels. As the water flows through dense vegetation, particles settle, and plants and soil absorb dissolved materials. During resting periods (typically 12–16 hours per day), organic materials are oxidised, and nutrients incorporated into biomass, microbially transformed or bound in the soil layer.

(Kadlec & Knight 1998)

Aquatic and wetland treatment systems are fundamentally different from upland systems because they are continuously flooded and typically develop anaerobic sediment and soil layers. The anaerobic environment precludes the use of terrestrial plants that rely on soil oxygen, but not anaerobic and aerobic assimilation processes in a single layered treatment system.

- **Facultative ponds** are one of the oldest and most widespread treatment technologies, often dominated by renewable energy from the sun and biota. They are designed to maintain a natural aerated layer over a deeper anaerobic layer. The aeration occurs through atmospheric oxygen diffusion and release of oxygen by algal photosynthesis in the water column. However, because of their reliance on algal growth as a means of removing BOD, there is a limitation on attaining low suspended solids outflow concentrations.
- **Floating aquatic plant systems** are ponds inoculated with floating aquatic plants. Typical plants include water hyacinth (*Eicchornia crassipes*) and duckweed species (e.g. *Lemna, Spirodela, Wolffia*). Floating aquatic plant systems are functionally different to pond systems because the photosynthetic component is provided by the blanket of floating plants on the water surface, not algae in the water column. Consequently, aerobic conditions are limited to the root zone of the plants, with the rest of the water column oxygen deficient or anoxic. Treatment in floating aquatic plant systems occurs through three mechanisms:
    - metabolism by the mixture of microbes attached to the plant roots suspended in the water column, or in the detritus on the pond bottom

- sedimentation of wastewater derived solids and in-pond produced biomass (dead plants and microbes)
- incorporation of nutrients in the living plants and subsequent harvest.

Floating aquatic plant-based systems are effective at reducing BOD and TSS, and may effectively remove nitrogen through denitrification processes. Total N (TN) and Total P (TP) removal is achieved through harvesting of the plants. However, these systems typically rely on just one, or a few, plants and they can therefore be susceptible to events that rapidly kill off the plant populations. For instance, water hyacinth is easily killed by cold weather. In addition, harvesting of biomass and maintenance of optimum plant growth can be a system management problem.

Wetland systems use rooted, water-tolerant plant species, and shallow, flooded or saturated soil conditions to provide wastewater treatment. The three basic types of wetland include natural wetlands, constructed surface flow wetlands, and constructed subsurface flow wetlands.

- There are many types of natural wetlands, but only wetlands with plant species adapted to continuous flooding are suitable to receive the continuous flows of wastewaters. Natural wetlands are also often protected, ensuring that if they are used as treatment wetlands, the influent water often has to be highly pre-treated and of high quality.
- Constructed wetlands mimic the treatment conditions found in natural wetlands, but can be created in almost any location, and used for primary or secondary treatment of a variety of waters.

(Kadlec & Knight 1998)

Most constructed wetlands are designed, built and operated with the intention of improving water quality. Properties that make wetlands attractive for pollution mitigation include:

- high plant productivity
- large adsorptive capacity of the sediments
- high rates of oxidation by microflora associated with plant biomass (biofilms)
- large buffering capacity for nutrients and pollutants.

Wetlands provide a diversity of niches and micro-environments whose processes operate against a background of changing environmental conditions, such as:

- **Diurnal changes:** For instance, lower night-time temperatures can slow microbial activity and abiotic chemical reactions. Photosynthesis adds oxygen to the water column by day, but this is depleted at night as organisms respire.
- **Seasonal changes:** For instance, growth and reproduction of wetland plants (and other organisms) is stimulated by changes in day length and air temperatures. Warmer temperatures lead to increased growth of wetland organisms, increased nutrient cycling and uptake. Dry periods accentuate organic matter decomposition.

(DLWC 1998)

Wastewater treatment wetland designs

Constructed wetlands are not considered suitable for the treatment of raw sewerage or raw industrial process wastewater. Some treatment of the wastewater is needed before the living organisms in the wetland are exposed to the materials within the wastewater stream. In designing constructed wetlands for the amelioration of treated municipal, agricultural or industrial effluents, the aim is to maximise contact between polluted water column and the bioactive components of the wetland, e.g. biofilms and sediments. The efficacy of contact is related to the flow path of the water, which in turn is related to the physical dimensions of the wetland, and the hydraulic residence time (DLWC 1998). Although wetlands must be individually designed for particular performance objectives and site constraints, designing constructed wetlands for the treatment of pollutants entails:

- sizing the wetland for a given flow-rate, mass loading, and pollutant removal efficiencies
- inlet and outlet structures for water level control, recycling, flow splitting and distribution
- flow path configuration
- depth variation within and between cells for better pollutant removal, flow distribution, macrophyte health and habitat diversity (if required)
- planting details (i.e. species, planting density)
- an operation and maintenance plan.

Constructed wetlands use natural processes to remove pollutants. These natural processes require energy, which is obtained from the sun through solar radiation. Thus, these systems require more land area and time to achieve the same results in pollutant removal than energy intensive technologies. Contact with biofilms on substrates such as plant stems and roots, gravel, soil or sediment, is particularly important because microbes do most of the pollutant transformation. Thus, the wetland design should aim to optimise, and then stick to, the theoretical hydraulic residence time.

Constructed wetlands for wastewater treatment can be categorised as free water surface (FWS), or subsurface flow systems (SSF). Both FWS and SSF systems can be combined in series or in parallel to achieve performance objectives. The sequence of the various components can be important in achieving performance objectives. That said, wastewater wetlands tend to be less dynamic than urban stormwater wetlands because of:

- little variation in inflow rates (relatively constant inflow, variation typically only a factor of 2–5 times)
- known pollutant loadings (variation typically only a factor of 2–5 times)
- single issue or otherwise clearly defined and focused objectives
- definitive water quality requirements set by licence.

FWS wetlands are land intensive, biological treatment systems, and are most appropriate for polishing secondary and tertiary effluent and for providing habitat. FWS systems are capable of removing organic material, suspended solids, phosphorus, heavy metals, and pathogens. The environment within a FWS wetland will generally be aerobic at or near the surface, becoming anoxic near bottom sediments. Level of aeration depends on:

- controllable factors, such as stratification, degree of mixing, turbulence, surface cover, and
- less controllable factors, such as temperature, sunlight (availability and penetration), wind speed, water birds and other animals.

Vegetation types and water column contact in constructed wetlands

Wetland type	Vegetation type	Section in contact with water column
Free water surface	Emergent Floating Submerged	Stems – limited leaf contact Root zone – some stems/tubers Photosynthetic parts, possibly root zone
Subsurface flow	Emergent	Rhizome and root zone

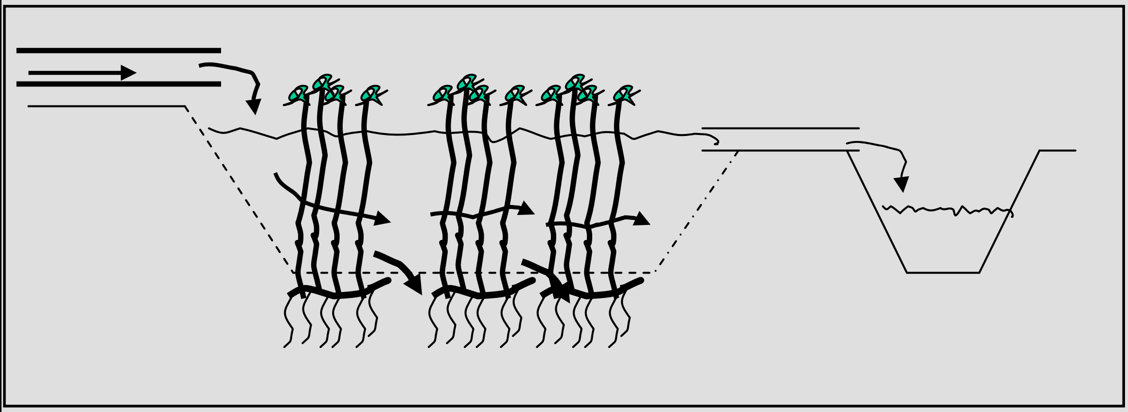

Figure 1. Systems with free water surface (FWS or SFW)

The main difference between natural and constructed treatment wetlands is the origin of their landform. Constructed wetlands (of whatever design) can be built at, above, or below the existing land surface if an external source of water (i.e. wastewater) is added. Essentially, FWS wetlands consist of:

- basins or channels with subsurface barrier to prevent seepage (e.g. synthetic or clay liners)
- soil or other suitable medium to support the growth of emergent vegetation
- wastewater that flows freely across the surface of the bed
- management of water flow to ensure water is kept at relatively shallow depth through unit.

In FWS systems, the water column (inflow water) containing particulate material and dissolved pollutants slows and is spread through a large area of shallow water and emergent vegetation. Essentially, the water column is in contact with plant surfaces, upon which microbiological films grow. Direct uptake of nutrients, ions and contaminants by plant roots is only really possible for floating or submerged species.

Uptake by emergent species will occur, but mineralisation of nutrients and other materials is necessary first, since they must move through the soil/sediment to reach the plant roots. The time required for this process is usually far greater than the residence time of wastewater in the wetland, and so pollutant removal by direct uptake by macrophytes is not significant in FWS systems.

- Shallow water depth, low flow velocity, presence of plant stalks and litter regulate water flow – in long, narrow channels this ensures plug-flow conditions.
- Particulates (total suspended solids) tend to settle in the quiescent conditions.

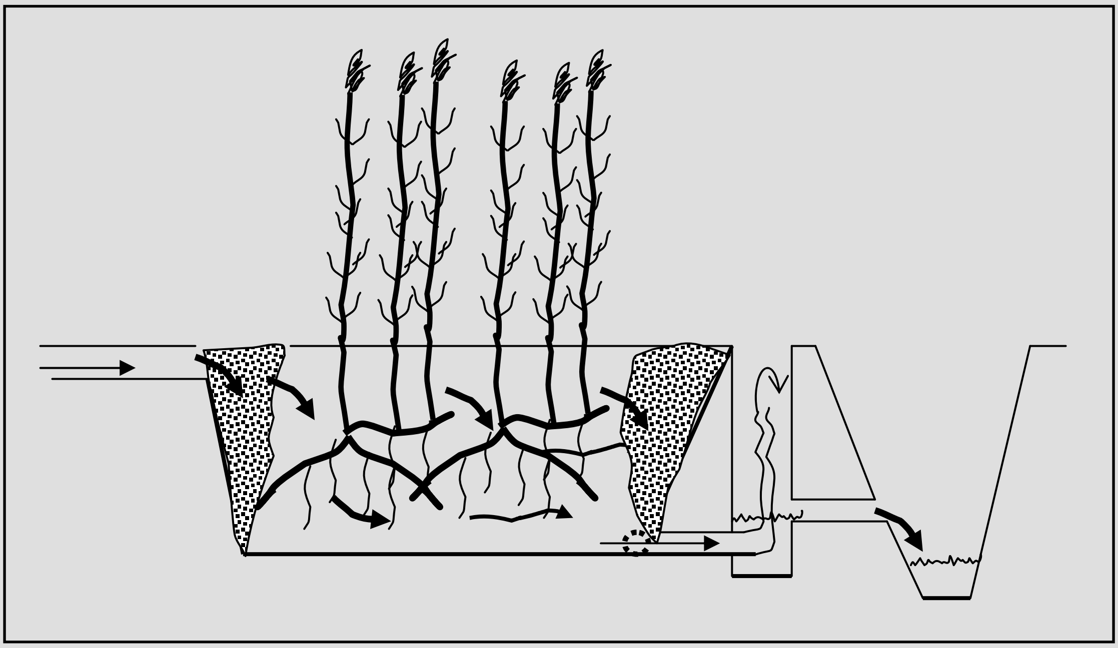

Figure 2. Systems with horizontal subsurface flow (SSF or HSSF)

The general concepts for subsurface flow wetlands are not that much different to those of surface-flow wetlands:

- basins or channels lined with non-porous barrier to prevent seepage
- soil or other suitable medium to support the rooted vegetation
- pre-treated wastewater fed in at one side of the system and flows slowly through a porous medium <u>under</u> the surface of the bed in a more or less <u>horizontal</u> path until it reaches the outlet. During this subsurface flow, the wastewater interacts with the mixture of facultative microbes living in association with the substrate and the plant roots. Settle-able and suspended solids not removed in pre-treatment system are effectively removed by filtration.

Vertical subsurface flow wetlands are essentially identical to horizontal surface-flow wetlands, with the major difference being the direction of water flow:

- basins or channels lined with non-porous barrier to prevent seepage
- soil or other suitable medium to support the emergent, rooted vegetation
- wastewater distribution system covers whole surface area of a sectioned bed (infiltration compartment)
- wastewater fed intermittently (in rotation) to each infiltration compartment, and water flows slowly <u>down</u> through a porous medium under the surface of the bed in a more or less <u>vertical</u> path until it reaches outlet (agricultural drainage pipes).

Wetland components

Wetlands are made up of a number of '**zones**' – a term used to describe the major functional units of the wetland, or the cells within a wetland. The zones themselves consist of various components, e.g:

- inlet zone – inlet structures and splitters box
- macrophyte zone – porous bed/substrate, open water (in FWS system), vegetation, islands (in FWS system), mixing baffles, flow diversion
- outlet zone – collection devices, spillway, weirs, outlet structures.

There is no 'typical' configuration. However, the cells of a constructed wetland for wastewater treatment, and the components within the cells, can be sequenced in a number of ways to achieve design objectives.

- **Cells in parallel** provide flexibility and redundancy of operation, so cells can be taken off-line for repair and maintenance. When one cell is taken off-line, flow is redirected to the other cells. During normal operation, the flow entering the cell is in proportion to the size of the cell, although it is possible to operate different cells with different hydraulic retention times (not a common mode of operation).
- **Cells in series** have the advantage of minimising short-circuiting of water flow, and can thus provide better overall treatment efficiency. Recycling opportunities between cells are also improved, as are opportunities for specifying treatment within individual cells, i.e. organic particles removed in cells preceding those designed for nitrogen removal. The system must be designed so that an individual cell can be bypassed for routine maintenance or repair.
- **Cells in parallel and series** can give both the operational flexibility of cells in parallel, and the treatment efficiency of cells in series.

There are some general features that most wetlands incorporate:

- Graded bed slopes to assist in water movement and self drainage (typically 0.1–1%). However, high slopes over long distances can lead to difficulties with plant establishment because of inappropriate water depths over the length of the bed initially.
- Capacity to vary operational water depth.
- Minimal number of stagnant zones and short-circuiting, encouragement of mixing. This can be done by designing cells in series, or using mixing baffles, or having zones of varying depths, or open water zones and/or flow diversion structures.
- A length:width ratio between 1:1 and 10:1.
- Flow distribution systems at inlet of each cell and multiple collection devices at outlet of each cell.
- Vegetated and open water zones to minimise short-circuiting, provide operational flexibility with recirculation, and maximise habitat diversity.

Treatment wetland zones and components

Zone	Components	Function
Inlet zone	Inlet structure	Convey flows across full width of each cell (e.g. tooth weirs, riser pipes, lengths of slotted pipes and hard bottomed weirs). Holes must be big enough to prevent blockage by algal growth. In SSF systems, large diameter gravel is used near the inlet system to prevent blockage.
Macrophyte zone	Porous media (in SSF wetlands)	Provides substrate with high hydraulic conductivity (ease of water flow); provides surface for growth of biofilms in permanent contact with wastewater; aids in removal of fine particles by sedimentation; provides support for development of root and rhizome systems of emergent plants.
Littoral zone	Reed beds	Provides for optimal plant growth and biofilm development. Plants should be compatible with design depth (i.e. 0.5–1 m in FWS systems). Diversity of plants increases habitat potential, although in some cases (i.e. SSF wetlands) monocultures are often used (with attendant risks of disease, destruction by parasites and weed invasion).
Deep water zone	The margin near the shore	Can provide excellent habitat for biota, and visual amenity. Steep bank slopes reduce area of littoral habitat. Littoral vegetation reduces bank erosion.
Outlet zone	Open areas of water >1 m deep	Can enhance natural processes operating within the wetland, including reducing short-circuiting by redirecting flow, preventing stagnation by allowing wind mixing of the water column; provide further opportunities for sedimentation, enable UV disinfection of pathogens, and provide habitat for wildfowl.
	Outlet structure	Small area of open water and filter prevents debris blocking outlet. Provide for control of depth of water in wetland, collection of effluent and samples.

(DLWC 1998)

Practical considerations when determining the area of open water relative to the area of reed bed in FWS system	
Objective	**Consideration**
Water quality	Wetland should be predominantly reed beds (and associated biofilms) for filtration and nutrient removal. Have bands of the same macrophyte positioned perpendicular to the stream flow. Different plant species provide different resistance to flow – thus monoculture bands planted across the stream flow reduce the potential for short-circuiting. Sections of deep, open water increases detention time, and allows for water-column mixing and pathogen kill. Flow diversions, often used in complicated, complex shaped reed beds, also increase retention time and reduce the potential for stagnant water areas.
Habitat diversity	Open water around habitat islands can provide protection for fauna from feral animals. Open water is needed to provide landing areas for birds. Reed beds can provide for macro invertebrate habitat.
Aesthetics/recreation	The greater the area of open water, the better the viewing. Passive recreation is enhanced by large areas of open water, although some reed beds can provide for visual balance.

(DLWC 1998)

Table 1. Overview of pollutant removal mechanisms in wetlands

Material	Removal process
Organic material (as measured by BOD)	Biological degradation, sedimentation, microbial uptake
Organic contaminants (e.g. pesticides)	Adsorption, volatilisation, photolysis, abiotic/biotic degradation
Suspended solids	Sedimentation, filtration
Nitrogen	Sedimentation, nitrification/denitrification, microbial and plant uptake, volatilisation
Phosphorus	Sedimentation, filtration, adsorption, plant and microbial uptake
Pathogens	Natural die-off, sedimentation, filtration, predation, UV degradation, adsorption
Heavy metals	Sedimentation, adsorption, plant uptake

There are six major biological processes of interest in the performance of constructed wetlands, namely:

- **Photosynthesis:** An activity performed by both wetland plants (macrophytes) and algae that adds carbon and oxygen to the wetland. Both carbon and oxygen drive the nitrification process. Plants also transfer oxygen to their roots, where it may leak into the area immediately adjacent to the roots.
- **Respiration:** An activity performed by all living organisms that converts (oxidises) complex organic carbon to simpler molecules, and ultimately carbon dioxide and water.
- **Fermentation:** The decomposition of organic carbon in the absence of oxygen to produce energy-rich molecules, such as methane, ethanol, and volatile fatty acids. Often undertaken by microbes.
- **Nitrification/denitrification:** A process mediated by micro-organisms that aids in nitrogen removal from the wetlands, often through volatilisation of inorganic nitrogen gas.
- **Phosphorus removal** in biofilms, and adsorption onto sediments.

Essentially, plants take up dissolved nutrients (and pollutants) from the water and use them to produce additional biomass. The nutrients are stored in underground storage organs when the plants senesce, and deposited in the sediments through litter and peat accretion when plants die.

Wetland micro-organisms found in biofilms attached to plant and other surfaces within the wetland are often considered to be the ‘engine’ driving treatment processes. Many of the micro-organisms that are found in constructed (and natural) wetlands are the same as those that are used in conventional water treatment systems. Many bacteria and fungi remove soluble organic material, coagulate colloidal material, stabilise organic matter and convert organic matter into new cell tissue and gases. However, the different types of micro-organisms have different tolerances and needs for dissolved oxygen, nutrients and optimal temperature ranges.

Chemical and biological processes in wetlands occur with rates dependent upon a number of environmental factors, such as temperature, oxygen presence and pH.

- Metabolic activity is reduced at low temperatures, reducing the effectiveness of uptake processes that rely on biological activity.
- Low oxygen concentrations limit processes involving aerobic respiration (and may enhance anaerobic processes).
- Many metabolic and chemical reactions are pH dependent, and are less effective if the pH is above or below an optimum range.

The capacity of a constructed wetland is limited in terms of the amount of water and amount of pollutants flowing through the wetland.

- **Hydraulic overload** occurs when the flow exceeds the design capacity, causing retention times that are too brief to enable effective pollutant removal.
- **Pollutant overload** occurs when, as the name suggests, pollutant load exceeds pollutant removal rates (capacity) within the wetland.

Table 2. **Effect of pollutant overloading on wetlands and wetland processes**

Pollutant	Primary effect	Secondary effect
Organic matter	Decomposition consumes oxygen in water, leading to anaerobic conditions	Reversal of many pollutant removal processes
Nutrients	Eutrophication, leading to algal blooms	Reversal of many pollutant removal processes, potential for accumulation of algal toxins in water column and sediments, dead algae increase BOD through decomposition, living and dead algae in water column increase total suspended solids concentration
Sediment	Blanketing of plants and biofilms	Reduced biological processes
Toxins	Kills or harms biota	Reduced biological processes, potential for bioaccumulation and biomagnifications

To summarise, the proper functioning of a constructed wetland for water treatment relies on the interaction of three components: wetland plants, water quality, and wetland design. It is to the first of these that we now turn.

3. *Arundo donax*

The giant reed (*Arundo donax*) is a perennial, herbaceous plant found in grasslands and wetlands over a wide range of climatic and habitat conditions. The giant reed is considered by some to be native to East Asia (Polunin & Huxley 1987), India (Dudley 2006) and the Mediterranean (Armstrong & Breadon 2006). The situation is confused because for thousands of years the giant reed has been cultivated in Asia, South Europe, North Africa and the Middle East. In the 19th Century, the giant reed was diffused widely in North and South America, and in Australia (Perdue 1958).

Although most commonly known as the giant reed, *Arundo donax* has many other common names, including:

English names	Other languages
• arundo grass • bamboo reed • Danubian reed • cane • cow cane • donax cane • giant cane • giant reed • Italian reed • Nalgrass • Provence cane • reedgrass • river cane • Spanish reed • Spanish Cane	In non-English speaking countries, the most widely uses names are translations of the simple epithets ‘cane’ or ‘common cane’. • Alokyu (Burma) • cana comum (Spanish) • canne de Provence (French) • carrizo grande (Spanish) • kalamos (Greek) • kasab (Egypt) • narkhat (Indian) • ngasau ni vavalangi (Fijian) • Pfahlrohr, Pfeilrohr (German) • Riesenschilf (German) • roseaux (French) • Spanisches Rohr (German)

(Bell 1997; Lewis & Jackson 2002; Perdue 1958; Weeds Australia 2006)

Arundo donax is the tallest (up to 10 m) of the six perennial, reed-like grass species that make up the *Arundo L.* genus (Bell 1997). The root system of *A. donax* consists of fleshy, compact masses of rhizomes from which rise tough, fibrous roots that penetrate deeply into the soil. Once established, *A. donax* forms large, dense clonal rhizome masses. The stems of *A. donax* have a diameter of 1–4 cm, are hollow with walls 2–7 mm thick, and are divided by partitions at the nodes which range in length from 12–30 cm (Perdue 1958). The main stems of *A. donax* commonly branch during the second year of growth. The leaves are 5–8 cm broad at the base and taper to a fine point. Flowers are borne on a large plume-like terminal panicle, dense and erect to 60 cm long, and produced in summer. Seeds are wind dispersed (Forestry Service 2006).

The giant reed has spread across the world, particularly in areas with a Mediterranean climate, but it has been reported that *A. donax* does not produce viable seed in most areas where it has been introduced (Perdue 1958). For instance, there are no records of *A. donax* seedlings in southern California, where it is generally assumed that it does not reproduce sexually (although this has not been confirmed). Consequently, the species is thought to spread primarily asexually by flood dispersal of stem cuttings and rhizome pieces. In this situation, the natural variability in existing populations of clones, as it is known, may occur due to spontaneous mutation followed by natural selection as a response to climatic stresses and to different environments, or by transferring part of the plant through the usual ways of diffusion. Very little under-story vegetation is found under *A. donax* due to its dense growth, and this reed does not seem to provide the structure required by riparian birds for perching and nesting.

Reports on the origin of this species is conflicting; some suggest that it is from locations around the Mediterranean (Armstrong & Breaden 2006; Hoshovsky 2003) and Madagascar (Armstrong & Breaden 2006). However, the consensus is that the species originates from Asia (most probably India) and has been cultivated for thousands of years throughout Asia, southern Europe, North Africa and the Middle East (Perdue 1958). The giant reed is now a common weed in Iran, Spain, Argentina, Chile, Dominican Republic, New Zealand and United States of America (Decruyenaere & Holt 2005). It was probably introduced into California in the early 1800s (Bell 1997).

Arundo donax does not readily produce viable seed in many locations (Perdue 1958) but there have been instances where it has grown from seed collected from Indian populations. Most reproduction occurs via rhizome which root and spread readily (Hoshovsky 2003). *A. donax* prefers well drained soils with abundant moisture, although it has also been reported to thrive in heavy clays (Hoshovsky 2003), and can spread from the edge of a water body to past the riparian zone (Dudley 2006). It grows well where the water table is at or close to the soil surface, and can tolerate excessive salinity (Perdue 1958), although perhaps only at the individual plant level rather than a stand of *A. donax*.

Arundo donax has an extremely fast growth rate under optimal conditions and growth rates of up to 5 cm per day, and 70 cm per week under favourable conditions (Perdue 1958). The giant reed can produce more than 20 tonnes per hectare above-ground dry mass or 8.3 tonnes of oven-dry cane per acre (Hoshovsky 2003; Perdue 1958). Concomitant with such fast growth rates is a high water demand, and *A. donax* can use as much as 2000 L of water per metre of plant (Purdue 1958). This is three times as much water as US native plants, and similar to the water use of rice crops. The high water use may make this species suitable for water treatment applications. High water use may also make *A. donax* a good species for rapid rotation with agricultural crops in areas with elevated water tables, provided its roots penetrate deeply enough to dry out the vadose zone to significant depths, and a market can be developed for the biomass produced.

Outside of Australia, *A. donax* has been used for erosion control (Perdue 1958), as an ornamental plant (Hoshovsky 2003), as thatching and lining of houses and storage bins (Hoshovsky 2003), and for musical instruments ranging from pan-pipes (Hoshovsky 2003) to bagpipes and bassoons (Bell 1997). The leaves, stem and rhizome have many other domestic uses such as to make baskets, fishing rods and arrows, for penning and feeding livestock, and as a medicine (Perdue 1958). In Italy, this species has been utilised industrially since 1930, when Snia-Viscosa registered a trademark to obtain cellulose pasta for the production of rayon viscose and paper (Costentino et al. 2006).

Recently, this species has been suggested as one of the most promising for energy and cellulose pasta production for the Southern areas of Europe (Cosentino et al.

2006; Ververis 2004). Traits that make such uses possible include its perennial nature, easy adaptation to different environmental conditions, high production of biomass, and low input requirements (Cosentino et al. 2006).

One of the goals of the bioethanol industry is to be able to produce ethanol economically from ligno-cellulose, and this requires knowledge of the ligno-cellulose composition of feedstocks. Ververis et al. (2004) report that *A. donax* has satisfactory levels of α-cellulose (~31–38%, depending on position in stem and if node or internode) and Klason lignin content ($\leq$20%) compared to those derived from softwoods and hardwoods. Neto et al. (1997) have characterised the polysaccharide composition of *A. donax* in different morphological regions of the plant. Glucose (25–33%) and xylose (24–28%) are the main sugars present in *A. donax*. Neto et al. suggest that *A. donax* could thus be used as a source of pentosans for the furfural-based industry, since this is a higher pentosan content than traditional sources such as corn-cobs, rice hulls and sugar cane bagasse. The glucose could, of course, be used for bioethanol production, as could the pentoses when economic C-5 fermenting organisms are found.

The giant reed has also been evaluated as a non-wood fibre source for pulp mills by Lewis and Jackson (2002), who report that *A. donax* was suitable for direct substitution for hardwoods in existing kraft mills without major equipment changes. For instance, the handsheet strength, burst, tensile and tear were all comparable with, or better than, those of wheat straw, kenaf and hardwood (Aspen kraft) pulp. Shalatov and Pereira (2002) noted that the stem of *A. donax* is similar to wheat straw and bamboo spp., in that it is morphologically heterogeneous, consisting of two botanically distinct parts: nodes and internodes. In other words, *A. donax* is hollow in internodes, but solid in nodes. Shalatov and Pereira further noted that stem heterogeneity has caused problems during pulping for other species. During their tests, some differences were observed in node and internode based pulp, e.g. papermaking properties and the brightness of unbeaten kraft pulps produced from internodes were higher than pulps made from nodes, reflecting the mass proportion of nodes and internodes in the stem of *A. donax*.

Bell (1997) suggests that *A. donax* provides little food for wildlife in California, and speculates that insects are sparse in sites dominated by giant reed because of the many chemical defences produced by the plant, e.g. silica, tritepenes, curare-mimicking indoles, hydroxamic acid and other alkaloids (Bell 1997, and references therein). This perhaps explains why the giant reed has not found more uses as animal feed. Hoshovsky (2003) reports that the use of Angora and Spanish goats is showing promise as an effective control agent for *A. donax* in California, so obviously some animals will eat this plant. Goats do, however, prefer woody vegetation over most grasses, so this observation is perhaps not surprising. Hoshovsky (2003) also reports that sheep can survive for extended periods on a strict diet of *A. donax*, and thus they may be a practical alternative to mowing as a form of weed control. Cattle are reported to not find the giant reed very palatable, but will graze it when other sources of fodder are not available, e.g. during dry seasons (Wynd et al. 1948). The plant is low in protein (confirmed by Neto et al. 1997), but high in phosphorus, even when grown on soils deficient in this nutrient. However, crude protein reached about 12% in the upper half of younger plants, being reduced to about 6% in the upper half of older plants. Both young and old plants contained about 3% protein in the lower half of the stems. Phosphorus shows similar patterns, reaching 0.15% in the upper half of young plants.

On the other hand, calcium and magnesium concentrations are greatest in the upper half of older plants. Early Australian research suggests the species was a suitable alternative fodder for pigs, cattle and horses, the smaller leafy variegated variety being preferred (Spafford 1941).

3.1 *Arundo donax:* Weed potential

The giant reed (*A. donax)* has been listed in the top 100 of the worst weeds in the world on the Global Invasive Species Database compiled by the Invasive Species Specialist Group (ISSG) of the IUCN Species Survival Commission (ISSG 2007). *Arundo donax* is also considered to be in the top 30 worst weeds in the world by the Weeds CRC (2005). That said, *A. donax* is not listed as a noxious or invasive weed Australia-wide, but is considered a naturalised invasive species in Queensland (no. 131 of the top 200 species in this category), and controlled on a regional and/or local basis in New South Wales (Table 3). *Arundo donax* is not listed as a noxious or invasive weed in Victoria (Faithfull 2006), and does not appear to have been considered as an imminent risk by the current *Victoria's Noxious Weeds Review* undertaken by DPI (2007).

Table 3. *Arundo donax* weed status in Australia (Weeds Australia 2006)

Weed Status								
	Vic	NSW	SA	WA	Tas	Qld	NT	ACT
A. donax		C3 (11) C4 (14)		Unass				

***NSW:** C3 = regionally controlled weed; C4 = locally controlled weed; (#) = number of local control authorities in which weed is declared.*

***WA:** Unass = plant species declared in other States and Territories that are not on the WA Permitted and Prohibited list, are unassessed and are prohibited until assessed via a weed risk assessment.*

Arundo donax has been observed in Western Australia, along the Yarra River in Victoria, the Torrens River in South Australia (Weeds CRC 2005), and in the Little Para estuary of South Australia. *A. donax* was established 150 years ago in South Australia for ornamental and fodder use (Williams et al. 2006) and in many areas for erosion control and ornamental use (Weeds CRC 2005). In Western Australia, *A. donax* is considered to be a garden escapee forming suckering clones around old settlements on roadsides, creek lines, wetlands and wasteland from Geraldton to Albany, and very common around Perth, where variegated leaf clones (var. versicolor) are frequent (Western Weeds 2006). There is no published distribution information in Victoria, although there are anecdotal reports of widespread distribution of small stands around Melbourne and Port Philip Bay, and elsewhere in the state.

Arundo donax is considered to have high weed potential because of its rapid growth rate and vegetative competitive nature (Weeds CRC 2005). These two factors alone can cause it to quickly dominate native vegetation in the USA (Hoshovsky 2003). Whilst seed dispersal does not appear to be a factor in the spread of this plant (Bell 1997), fragmented stems and rhizomes readily take root, particularly after a flood where they have been broken off and dispersed downstream. It is suspected that *A. donax* may release toxins into the water to prevent other plants establishing (Weeds CRC 2005). The giant reed is considered an invasive pest in the United States, being well established in warm, coastal freshwaters from Maryland to northern California (Bell 1997). This plant is considered the greatest threat to riparian vegetation in coastal southern California (Bell 1997). *Arundo donax* is not known to have any natural predators in North America, and it is uncertain what limits its population in its native habitat (Bell 1997).

Very little under-story vegetation is found under *A. donax,* due to its dense growth, and this reed does not seem to provide the structure required by riparian birds for perching and nesting. Herrera and Dudley (2003) studied the impact of *A. donax* on riparian arthropods and found that *Arundo* vegetation supported significantly less terrestrial arthropods than was associated with native vegetation. Bell (1997) concluded that *A. donax* was unlikely to provide food or nesting habitat for animals or birds native to America. The giant reed out-competes species such as willows (Salix spp.) that are native to America. Since willows are an exotic pest in Australia, it might also be assumed that *A. donax* will out-compete native Australian riparian trees and shrubs under suitable climate and habitat conditions.

Although *A. donax* was used to control erosion along ditches in south-west America (Perdue 1958), it has escaped cultivation areas and become established in ditches and streams, choking irrigation ditches to the point of reducing their water carrying capacity (Hoshovsky 2003). Despite this weed potential, Hoshovsky (2003) reported that little had been published regarding control strategies for the species. Hoshovsky (2003) suggested that a number of approaches, such as slashing, hand pulling and digging, chopping or mowing, burning, prescribed grazing, biological control and chemical control could be employed to reduce populations or densities of *A. donax*. Armstrong and Breaden (2006) suggest application of glyphosate to either cut stump or foliage. Bell (1997) found that *A. donax* responds quickly after fire and can easily out-grow Californian native species, therefore burning would need to occur a number of times whilst ensuring native species were not disadvantaged. Hoshovsky (2003) concluded that in order to eradicate the plant, the entire rootstock would need to be removed as it reproduces vegetatively from the rhizome and can be spread by rhizome fragments dispersed along watercourses. Bell (1997) suggested that the best way of achieving this is via chemical control using systemic herbicides. The most effective way of controlling *A. donax* in Australia has been to remove it from the entire river system whilst populations are small and preventing re-establishment through habitat restoration and public education regarding the distribution of the species (Weeds CRC 2005).

Despite having been present in Australia for at least 150 years, and having a number of qualities that make it an aggressive invasive species elsewhere in the world, *A. donax* has not yet achieved formal noxious weed status. Certainly it has not come to dominate riparian zones in the manner that some suggest (e.g. Weeds CRC 2005) in Victoria. This is perhaps due to climatic and ecological differences between southern Australia and the southern USA. The giant reed survives in areas with annual precipitation of 300–4000 mm, and grows in a wide range of soils, although it prefers well-drained soils with abundant moisture, and pH of 5–8.7. These requirements would seem to be readily available in Victoria, but since the giant reed does not propagate by seed, but rather spreads rapidly following flood events, perhaps changed river management in southern Australia in the past 100 years (river regulation and fewer flood events), and regular droughts have limited its ability to spread? Although drought causes no great damage to two- to three-year old stands of giant reed (Perdue 1958), *A. donax* can be seriously retarded by lack of moisture during its first year. The giant reed's ability to tolerate extreme drought is due to the development of coarse, drought-resistant rhizomes and deeply penetrating roots that can reach moisture at depth, but intermittent river flows followed by drying conditions again perhaps limit its ability to spread.

3.2 Use of *Arundo donax* in constructed wetlands

There is limited information available relating to the use of *A. donax* in constructed wetlands. In some ways this is surprising, since *A. donax* has a number of characteristics that appear to make it suitable for constructed wetlands (Table 4). For instance, the plant is easily propagated from rhizomes and stem plantings. The species is reported to tolerate excessive salinity levels (Perdue 1958). Rhizomes are produced on or near the soil surface, although data and information on the depth of rhizome formation has not been reported. Shoots and roots emerge from the rhizomes and the roots are reportedly able to penetrate to significant depths to obtain water contributing to their drought resistance particularly after the first year of growth (Perdue 1958). Pests and diseases are not known to affect the species and the only risk after the first year of growth is frosts early in the growing season, which can burn the new season's growth (Perdue 1958).

Williams et al. (2006) investigated the potential of using *A. donax* for wastewater treatment and pulp/paper production in South Australia. Although this research was not conducted in a constructed wetland, rather on an established dryland planting of *A. donax* over thirty years old, Williams et al. were able to conclude that the biomass yields exceeded that produced by other irrigated effluent crops, such as cereals, forage and hardwood plantations. For instance, Williams et al. (2006) reported that following clear-felling to 10 cm, within the first year this established stand of *A. donax* when irrigated with wastewater produced up to five times the biomass of Eucalyptus hardwoods in southern Australia. However, the authors conceded that the long term (20 years) productivity still needs to be determined. The weed risk of the species was not discussed in the paper, although the conclusion was made that the risk would be minimal if managed appropriately (Williams et al. 2006).

Table 4. Advantages and disadvantages of the species with respect to its use as a plant in constructed wetlands for wastewater treatment

Advantages	Disadvantages
Fast growth rate	Weedy potential
Does not appear to be viable from seed (reduced risk of off-site dispersal)	Threat to riparian vegetation
Limited number of pests	Fire hazard
High water consumption	Tolerance to continuous wetting unknown
Appears tolerant of high salinity (still to be confirmed)	Salinity tolerance unknown
Regenerates after fire from rhizomes	
Many potential uses for above-ground biomass	
Easily propagated from rhizomes	

Karpiscak et al. (1996) reported the successful incorporation of *A. donax* into multi-species free water surface wetlands in Arizona. However, while the authors reported good removal of many of the water quality parameters investigated, they did not mention whether there was any change in species distribution within the raceways. This has been seen in other wetlands (e.g. in the wetlands described by Allinson et al. 2005), and from both a risk management and wetland management perspective, it would be good to know if *A. donax* eventually came to dominate the raceways, or could the cattail (*Typha domingensis*), bulrush (*Scirpus olneyi*), black willow (*Salix negra*) and cottonwood (*Populus fremonti*) compete with the giant reed, or, indeed, was active management required to maintain species diversity?

The construction and operation of another free water surface wetland incorporating *A*. *donax* was reported by Manios et al. (2002). This wetland, built on the island of Crete to service a local village (population ~700, although the wetlands was designed for a population of 1200), used *A*. *donax* and *Typha domingensis* (cattail) for pragmatic reasons – they were the two most common emergent macrophytes found in local lagoons and rivers. Manios et al. report that the 'development of *Arundo donax* was so massive…. That it became impossible to enter the wetland and undertake a thorough [scientific] investigation.' Perhaps a salutary warning from these authors to those considering using the giant reed in a treatment wetland, particularly if species diversity is important? That said, other plants were found in the wetlands, particularly along its margins, and the dense matrix created by the giant reed's stems (70–90/m^2) and leaves, produced an excellent physical barrier for deposition of suspended solids.

Abissy and Mandi (1999) also explored the use of *A. donax* to treat municipal wastewater in Morocco in what was effectively a dryland planting of this reed, although the authors describe vertical flow through their beds. The two beds planted with *A. donax* were compared with two unplanted controls. After batch feeding raw effluent into the beds for two years, and monitoring inflow and outflow for organic loads, phosphorus and nitrogen over that time, the authors report no difference in removal of TSS or COD. This latter is perhaps not surprising since vertical flow removes the effluent from the primary site of biological remediation in wetlands, namely the biofilms that form around the macrophyte stems, and thus COD and TSS removal were primarily due to physical processes. The planted bed did, however, facilitate infiltration throughout the experiment, while in winter the control bed became clogged, with the former benefit perhaps a result of the greater porosity imparted by the plant roots. Nutrient and pathogen removal in the planted beds was acceptable, but conductivity, sodium and chloride concentration increased through the planted bed, perhaps a result of the giant reed's high water use concentrating these materials in the vadose zone.

Many wastewaters contain contaminants other than nutrients and suspended solids, including metals. Some cycling of metals occurs within wetlands, for instance through resuspending of sediments, soils or peat/litter (within which, or adsorbed to, metals reside), or through uptake (passive and active consumption) by organisms followed by release on death and decomposition. Removal can be up to 99% effective in some wetlands. There are three main removal processes (DLWC 1998):

- Adsorption to soil, sediments or organic particles. Adsorption (binding) processes are arguably the most important removal processes for metals in wetlands. Metals are positively charged in solution, and they are readily adsorbed to particles with negatively charged surfaces. Metals can also form complexes with organic materials (ligands). The particles are then removed through sedimentation processes.

- Precipitation as insoluble salts. The carbonates, bicarbonates, sulfides and hydroxides of many metals are highly insoluble in many aquatic environments. Metals reacting in the water column to form insoluble compounds will be removed from the water column by precipitation.
- Uptake by bacteria, algae and plants. This process may affect wetland food chains.

There are no reports of the use of *A. donax* in constructed wetlands for the removal of metals per se. However, Papazoglou et al. (2005) investigated the feasibility of using the giant reed as a means of utilising metal contaminated land in a productive manner, in this case the production of biomass for fuel. Although a pot experiment mimicking dryland culture, Papazoglou et al. found that high concentrations of nickel (Ni) and cadmium (Cd) (up to 500 ppm Ni and 350 ppm Cd respectively) had no apparent effect on plant growth (biomass production) or photosynthesis. The authors report that metals accumulated in the surface layer of the soils in the pots, but since metal concentrations in plant tissues was not determined, it is not known if the plants excluded the metals or accumulated them. However, the study did highlight the potential for *A. donax* to be cultivated productively as a bioenergy crop on contaminated land; potential that would be further enhanced if this species is shown to be tolerant to other metallic pollutants of soils (e.g. arsenic, lead).

4. Dairy processing industry effluent characteristics

In 2003–04, the Closing the Loop project undertook a survey of wastewater and organic waste management practices in 24 dairy factories, processing more than 95% of the total milk production in Victoria. In 2007, we undertook a second, detailed survey of waste production and management practices in the Victorian dairy industry using the methods used by the Closing the Loop Project in 2003. The survey was conducted through a targeted questionnaire focusing on solid and liquid waste management practices in Victoria's 24 main dairy factories, and assessed the type of production facility, chemical usage, water usage, wastewater and soil waste generation, current waste management practices and perceived waste problems. In short, the survey found:

- In 2007, 75% of the factories approached completed the survey to a greater or lesser extent. On average these 18 factories process over 5.3 billion litres of milk per year. The identified total annual costs associated with waste management for those factories surveyed was almost $28 million (cf. $37 million in 2004). Included in waste management costs are those for the approximately 8000 t/year of CIP alkali and 3000 t/year of CIP acid cleaners consumed (at a cost of more than $8 million). The amount spent on cleaning agents is almost half of that reported in 2003. This may be a result of improvements in environmental performance producing significant financial savings, but may also reflect reduced need for cleaning agents as a knock-on effect of continued drought.
- Collectively, in 2007 the total amount of water consumed annually by the Victorian factories was some 6948 ML. Proportionally, this is not dissimilar to the amount consumed by the 24 factories responding to the 2003 survey (~ 10,538 ML). However, the proportion of town water consumed has gone down (33% in 2007, cf. 61% in 2003).
- In 2007, collectively the 18 factories discharged a total of 8140 ML of wastewater. Proportionally, this is not dissimilar to the amount discharged by the 24 factories responding to the 2003 survey (~ 10,312 ML in 2003). The water was discharged to: surface-waterway (12%), land (53%), sewer (33 %), and wetlands (2%) (in 2003 the breakdown was 13%, 44% and 43% respectively).
- The most common biological process for wastewater treatment is still aerobic digestion, followed by anaerobic digestion (33% of factories), and dissolved air flotation (33% of factories). Disturbingly, 16% of respondents reported no treatment of wastewater before it was discharged.
- No factories provided enough data to conduct a reliable sodium balance, but in general sodium enters the factory in much the same way as in 2004 (i.e. either in milk, as CIP chemicals, or salt). A significant proportion of this salt leaves factories in the wastewater.
- The most common method of disposal of organic solid wastes was as stockfeed to piggeries, while some were sent off-site for composting or applied to land as a soil ameliorant/fertiliser.

The 2007 survey provides a basis for sizing a constructed wetland for a ‘typical’ dairy processing factory, and modelling nutrient removal for the Victorian dairy industry as a whole, and could be used as baseline data in future studies comparing national and international achievements.

- The key characteristic for sizing a wetland is daily average flow. In 2007, collectively the 18 factories discharged approximately 8140 ML of wastewater, or an average of 452 ML per factory. This equates to an average daily flow of 1.2 ML (assuming year-round flow).
- The data provided by factories for the key characteristics required for modelling wetland removal efficiency, namely BOD, N, P, and suspended solids, is variable (Table 5), perhaps reflecting both the different treatment processes within the plants but also the different products produced by each plant. However, it is within the capacity of constructed wetlands to remediate these wastewaters, given sufficient wetland size, water retention time, wetland porosity etc.

Table 5. Average dairy processing factory wastewater quality (as reported to the author in his Closing the Loop survey)

	Wastewater quality (average reported by each factory)										
Identity	**TSS (mg/L)**	**TDS (mg/L)**	**OG/F (mg/L)**	**BOD_5 (mg/L)**	**COD (mg/L)**	**Phosphate P (mg/L)**	**Total Kjeldahl N (mg/L)**	**Na ion (mg/L)**	**SAR**	**pH**	**Temp (°C)**
1	400	-	-	1700	2800	45	90	520	-	8.0	15
2	1200	2550	632	4300	6375	54	130	240	-	10.0	-
3	30	-	-	15	-	20	50	-	25	8.5	30
4	142	4	5	824	-	11	34	46	-	7.2	26
5	147	2140	237	117	538	47	124	616	6.9	6.9	30
6	645		-	27	153	8	27	150	6.7	7.8	-
7	2300	2500	1000	4000	-	-	200	300	-	8.0	25
8	19	1258	-	11	67	3	11	204	8.6	8.3	25
9	697	1945	255	1896	3441	19	75	321	-	11.6	38
10	100	2900	-	30	100	80	7	600	-	6.8	30
11	37	-	-	5	230	5	16	874	22.9	9.0	-
12	518	-	-	2150	4250	43	97	444	-	8.3	-
15	1385	1835	1100	-	4895	18	84	-	-	12.0	<38
16	22	2117	-	7	1334	6	4	675	32.6	9.2	17
17	1519	-	-	4155	-	-	186	-	-	6.6	-
18	1400		200	3000	5000		45			10.6	
Average	**660**	**1916**	**490**	**1482**	**2432**	**28**	**74**	**416**	**17**	**8.7**	**28**

TSS = total suspended solids; TDS = total dissolved salts; OG/F = oils, grease and fats

5. A constructed wetland for the 'average' dairy factory

Constructed wetlands are not considered suitable for the treatment of raw sewerage or raw industrial process wastewater. Some treatment of the wastewater is needed before the living organisms in the wetland are exposed to the materials within the wastewater stream. In designing constructed wetlands for the amelioration of treated municipal, agricultural or industrial effluents, the aim is to maximise contact between polluted water column and the bioactive components of the wetland, e.g. biofilms and sediments. The efficacy of contact is related to the flow path of the water, which in turn is related to the physical dimensions of the wetland, and the hydraulic residence time (DLWC 1998). Although wetlands must be individually designed for particular performance objectives and site constraints, designing constructed wetlands for the treatment of pollutants entails:

- sizing the wetland for a given flow-rate, mass loading, and pollutant removal efficiency
- inlet and outlet structures for water level control, recycling, flow splitting and distribution
- flow path configuration
- depth variation within and between cells for better pollutant removal, flow distribution, macrophyte health and habitat diversity (if required)
- planting details (i.e. species, planting density)
- an operation and maintenance plan.

It is beyond the scope of this review to produce a detailed design plan for a wetland, since these are all site specific. However, with the information we have – i.e. water quality and flow averages – it is possible to assess a generic wetland. There are three basic methods for sizing constructed wetlands for wastewater treatment:

- **'Rule of thumb' method:** Quite simplistic but provides a useful guide for preliminary sizing. In essence, the area required for the wetland is equal to 10–20 m^2 per m^3 of effluent per day.
- **Reed's method:** Considers wetlands to be attached growth biological reactors, and uses first-order plug flow kinetic models as the basis for performance equations. Reed's equations are based on the volume of the wetland and the average water temperature.
- **Kadlec and Knight's method:** Also uses first-order plug flow kinetic models as the basis for performance equations. However, Kadlec and Knight's equations are based on the area of the wetland, and the average water temperature is only considered significant for nitrogen removal.

(DLWC 1998)

Using the 'rule of thumb' method, and an average daily flow of 1.2 ML per day (1400 m^3 per day), gives an upper and lower range for the size of a generic constructed wetland to treat 'average' daily flow from a dairy factory of 14,000–28,000 m^2. It should be noted that this is an approach that has been used quite successfully in the U.K. for several hundred horizontal flow SSF systems planted with *Phragmites australis*, although it is debatable how much optimisation of this method there has been.

Having estimated the size of the wetland, perhaps the best next step is to make some assumptions about desirable treatment performance, and use Reed's method, and/or Kadlec and Knight's method to see if a wetland of the desired size can effectively treat the wastewater. Both methods consider wetlands as attached growth biological reactors, and therefore use first-order plug flow kinetic models as the basis for their performance equations. First-order kinetics simply means that the rate of removal of a particular component is directly proportional to the remaining concentration of the component. The main difference between Reed's approach and that of Kadlec and Knight is the basis for the rate constant. Reed's equations are volumetric and temperature dependant. In simpler terms, the calculations are based on the available volume of the wetland, and the average water temperature. Kadlec and Knight's equation is area dependant, so the rate constant is related only to the surface area of the wetland, and temperature changes are considered significant only for nitrogen removal. Kadlec and Knight also include a minimum possible pollutant concentration in their equations, whereas Reed sets minimum pollutant concentrations to be used as checkpoints after calculations (DLWC 1998).

For the purpose of this work, both Reed's and Kadlec and Knight's methods were used in an iterative manner. For instance, some initial design objectives were assumed. These were primarily based on the reduction of a number of water quality parameters: TSS, TP, TN, ammonia and BOD. Since the dairy factories did not report ammonia concentrations in their effluent, this parameter was guesstimated for the sizing process by assuming all nitrogen was converted to ammonia. The basic parameters used were, therefore:

- average flow of (Q) 1400 m^3/d (based on dairy factory WQ data)
- wetland area of 14,000, 21,000 and 28,000 m^2 (total area of wetland based on 'rule of thumb' sizing method)
- average depth of 0.2 m (likely maximum depth tolerated for extensive time periods by *A. donax*, although this needs to be verified experimentally)
- hydraulic residence time of 20 days (close to that of Masterfoods' wetlands in Ballarat treating wastewater of not dissimilar WQ)
- porosity – i.e. the space available for water to flow through the wetland – of 0.5 (assume moderately dense *A. donax* stands)
- influent data representative of 'average' dairy factory wastewater quality provided in 2007 (Table 5)
- assumptions on treatment efficiency. For instance, we wanted a 95% reduction in current BOD (from 660 to 10 mg/L), 95% reduction in TSS (from 200 to 10 mg/L), to reduce TP by 80% (from 16 to 5 mg/L), and TN by 85% (from 74 to 11 mg/L).

The first observation made was that the treatment efficiency assumptions were too demanding. For instance, wetlands with an effective area of 14,000, 20,000 and 28,000 m^2 would not effectively treat the 'average' influent. For P, the minimum achievable concentration was 16–21 mgL^{-1}. For TSS, the minimum achievable concentration was 89–82 mgL^{-1}. The theoretical retention time (<1 day) was well below the time required to remove BOD from the effluent. The calculated areas required for denitrification and ammonia removal were both well below the size of the system. The area required to remove BOD was also much higher than the target area.

By using Kadlec and Knight's method, the background levels for TSS and BOD in our model wetland were calculated. Target effluent concentrations were then modified to try to improve treatment efficiency, by raising the target concentrations to above background wetland concentrations. The modification of target effluent characteristics made little difference to the outcome (Reed's method). Essentially, the flow rate and water depth combine to produce a very rapid flow through the wetlands, even at low porosities. This provides very little time for sedimentation to reduce TSS, nor biological processes to reduce BOD and P. Kadlec and Knight's method does, however, provide a solution – increase the size of the wetland, to approximately 7.4 ha. While such an acreage would provide additional opportunities for the re-use of the *A. donax*, whether for garden stakes, stationary energy or liquid biofuel, this is unlikely to be possible for most dairy factories.

A number of things can be said about the modelling outcomes. The first is that the composition of waste streams differs from one plant to another, so there is no single universal design for the problem. Second, the modelling relied on 'average' dairy factory WQ data and the assumption that a free water surface wetland would be used. In reality, a wetland design would be produced using actual factory WQ data, with the type of flow based on site limitations, e.g. amount of available land. The latter may sometimes favour a free water surface wetland, at others a subsurface flow wetland, and in other cases a more elaborate design with reed covered shallow zones alternating with deep water zones. This latter type of design would provide increased detention time, and additional sedimentation and oxygenation, leading to improved treatment in a smaller area. Regardless, it would be possible to determine a cost-effective management approach by on-site visits, desk-top assessments, lab-scale experiments and later, plant-scale testing.

6. Conclusions and recommendations

This is the final report of a desk-top study designed to provide 'proof-of-concept' for the use of *A. donax* in constructed wetland systems designed to remove contaminants from dairy processing factory wastewater streams. Activities were therefore restricted to information collection, collation and evaluation. No field or laboratory activities were planned or have been conducted.

The following conclusions and recommendations can be made with respect to the first two project objectives, namely:

1. **Critically review existing information/studies related to the use of *Arundo donax* in industrial wastewaters, and any political/legal restrictions there might be to their use in Victoria.**

2. **Investigate the potential use of *A. donax* to treat dairy factory wastewater streams.**

The giant reed (*A. donax)* is a perennial, herbaceous plant found in grasslands and wetlands over a wide range of climatic and habitat conditions. The giant reed is found in most parts of Australia, including in Victoria, but is not listed as a noxious or invasive weed Australia-wide, although it is locally declared in New South Wales and thus its use is prohibited in Western Australia. The giant reed is not a declared weed in Victoria, and is apparently readily available from a number of garden suppliers. However, *A. donax* has some traits, such as fast growth rate, diffusion via flood-mediated rhizome dispersion, rapid re-growth after fire, and invasion of riparian zones that make it a potential weed. Even a cursory search for this species on the internet will return a large number of sites warning of the weed potential of the giant reed. Therefore, before *A. donax* is used in constructed wetlands in Victoria, South Australia, Queensland, the ACT, Northern Territory or Tasmania, consideration should be given to a detailed survey of its distribution within the relevant State. Such a survey should include an ecological assessment of local and/or regional adaphic and biotic factors that may constrain or promote its ability to become a weed.

Arundo donax has some characteristics that make it suitable for use in constructed wetlands for wastewater treatment. These include its fast growth rate, high water consumption, apparent salt tolerance (still to be confirmed), ease of propagation from rhizomes, limited reproduction from seed (reduced risk of off-site dispersal), limited number of pests, and the many potential uses for above-ground biomass. There is limited information on the use of *A. donax* in constructed wetlands, although the giant reed has been planted in several research and treatment wetlands (e.g. in Arizona and Crete). Very little treatment performance data is available for these wetlands, although the tendency for impenetrable stands of *A. donax* to rapidly dominate reed-bed systems has been noted.

Constructed wetlands are currently not able to remove sodium originating in factories and associated anaerobic water treatment plants. However, finding plants able to tolerate high salt loads could facilitate the use of constructed wetlands to ameliorate the organic and nutrient loads being discharged by factories. No detailed information is available on *A. donax* salt tolerance. There is thus not enough information to adequately assess the advantages and limitations of *A. donax* compared with other common wetland plants (e.g. *Phragmites australis)*. Consideration should be given to the establishment of pilot scale wetlands using *A. donax* to:

- examine the effectiveness of the giant reed (*A. donax*) in stripping nutrients and organic material from effluent by evaluating chemical transport, assimilation and release in pilot scale constructed wetlands, and in comparison with the common reed (*Phragmites australis*)
- assess the salt tolerance of *A. donax*
- examine options for the sustainable re-use of the biomass produced by *A. donax*
- investigate management techniques to minimise risk of escape of *A. donax* from constructed wetlands.

3. To design modular systems for the removal of Na salt from dairy factory wastewaters (including chemical analytical and biomonitoring techniques).

The concentrations of the key water quality characteristics required for modelling wetland removal efficiency, namely BOD, N, P, and suspended solids, is variable, perhaps reflecting both the different treatment processes within the plants but also the different products produced by each plant. However, in most cases it is within the capacity of constructed wetlands to remediate these wastewaters, given sufficient wetland size, water retention time, wetland porosity etc. Standard sizing methods were used to assess the use of *A. donax* in constructed wetlands to treat dairy factory wastewaters. The modelling relied on 'average' dairy factory water quality data and the assumption that a free water surface wetland would be used, and resulted in a rather large (~7.5 ha), shallow wetland. In reality, a wetland design would be produced using actual factory water quality data, with the type of flow based on site limitations, e.g. amount of available land. The latter may sometimes favour a free water surface wetland, and others a subsurface flow wetland, and in other cases a more elaborate design with reed covered shallow zones alternating with deep water zones. This latter type of design would provide increased detention time, and additional sedimentation and oxygenation, leading to improved treatment in a smaller area.

4. Develop linkages and seek co-funding for the construction/validation phase of the project from potential co-investors.

A number of approaches were made to dairy and other food processing companies in southern Victoria in the early stages of the project. The outcomes were reasonably positive, with in-kind support likely to be available (space, on-site support for qualitative monitoring of systems, provision of water, power etc), but direct financial support (cash) was unlikely. At this stage, small-scale laboratory and trial demonstrations will be needed before the dairy industry will consider this technology further.

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