SUSTAINABLE OPTIONS FOR SPORTS FIELDS

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Executive Summary

With water shortage and climate change becoming a critical global issue the need to reduce potable water usage and utilize non-potable water for non-potable use is increasing. An investigation of potential options for sportsgrounds has been performed as part of a study into sports field irrigation sponsored by the Victorian government's Smart Water Fund. This document represents part of this investigation and is aimed to guide water authorities, local councils and ground managers in the making decisions with regards to sustainability of sports facilities. In brief it looks at: different turf types with regards to water usage, suitability and injury concerns; irrigation concerns with scheduling and estimating water requirements; irrigation water delivery and storage; potential health impacts of different water parameters, to humans, turf and soil; perceptions with regards to water use; and alternative water sources.

A range of different warm- and cool-season turf were presented and a summary of their tolerances provided. Cool-season turfs have been typically associated with sports turf in Melbourne due to general temperature conditions, however they are more water hungry. Typically they are more cold and frost tolerant than other turfs and more tolerant to close mowing and shade. In general warm-season turfs have been adapted for warmer environments and utilize less water. They are typically more heat and drought tolerant, more salt tolerant and more wear tolerant. The main drawback is their poor cold tolerance and tendency to enter a dormant state in winter. This leads to loss of colour (generally towards a white or brown) and a loss of wear tolerance that is perceptually a negative for this class of turfs. Some species, particularly hybrid couches, are able to overcome this however and other options such as overseeding also provide potential solutions.

The effects of different natural turfs and soils on play properties such as ball bounce resilience and ball roll resistance were presented and generally showed little difference between warm- and cool-season turf (it must be noted however that studies on warm-season turfs are rare). In terms of injury rates one Australian study showed a slightly increased injury rate on some warm-season turfs, although the increase was small.

Artificial turf is becoming more popular and in its third generation is considered aesthetically pleasing. Its main deficiencies come in its perception by players and other users, the heating of the surface and the chemicals that can be leached from it. Players generally perceive the surface to be more dangerous. Studies have generally shown that injury rates do not increase on artificial turf, although the injury type changes. Having said this, minor injuries such as cuts and abrasions tend to be more common, but go unreported. It is these minor injuries that effect players perceptions and ultimately impacts on the way they play. Users have been shown to adapt to the new surface and over time play is less affected. More important was the impact on player endurance. To reduce major injuries, such as concussions, artificial surfaces are generally less hard and more "springy" than natural surfaces. This leads to players tiring more quickly and potentially impacting on the speed of a game.

The lack of evaporation from an artificial surface also gives rise to a difference in surface temperature. Surface temperatures on artificial turfs have been reported as high as 90

°C. This has to be overcome by applying water to the surface prior to use to drive evaporative cooling of the surface.

Releases of chemical from artificial turfs have caused significant grass roots campaigns against them in some parts of the world. In particular the concern is with volatile organics that can be released from the turf and the supporting infill. In general no evidence has been found that these chemicals affect players, but the community concern remains. Of greater importance is the need to capture stormwater from the field to prevent the leaching of these compounds and zinc to the environment.

The effective estimation of irrigation requirements is important to minimise the amount water used. Unnecessary over-irrigation can lead to wasted water, increased losses of nutrients and pollution of waterways. Two weather-based models for estimating irrigation requirements were presented. Although the results from each were different the estimation in general was proportional and either technique would be sufficient. Techniques for measuring soil moisture content were also presented and it was also shown that with the potential exception of heat capacity-based sensors they are all suitable for irrigation scheduling.

Irrigation delivery is one area where significant amount of water can be wasted. The less expensive techniques are typically more prone to wastage and human error than more expensive technologies. In general, water savings have been sometimes seen for subsurface drip-irrigation up to about 50%, while subirrigation has shown potential water savings of up to 90%. Both systems do however require significant capital expense and while maintenance requirements are generally lower, where they are required they can be quite extensive due to the systems underground location.

While storage of irrigation water in a tank seems reasonable, many alternative water sources are available in winter while the water is needed in summer. Other water sources provide water regularly when it is not always needed. To optimize the efficiency of water provided to the field, large water storages may be required. Tanks are generally too expensive for this. Artificial lake storage and aquifer recharge are two other options that may prove more appropriate for large storage where they can be made available. They both can lead to some decrease in the stored water quality however and this must be considered in case treatment is again necessary before use.

Impacts on turf and soil health from irrigation water come primarily from chemical sources. Salinity, boron, metals, oil and grease are four of the more significant ones. Salinity, in particular the ratio of sodium to magnesium and calcium can bring about significant changes in soil chemistry ultimately leading it to structural collapse and preventing water penetrating into the soil. This ultimately leads to turf death. High salinity irrigation waters should not be applied to clay soils and are best suited to soils classified as sandy loam or coarser.

Boron tolerance in turfs is quite high however boron from desalinated seawater may still be significant. Where boron is a problem, removal of clipping after mowing can reduce the impacts somewhat. Some metals, particularly copper and zinc, are present in potentially toxic concentrations to turf in irrigation water. Avoidance of sources of these contaminants is important or else the soil will need to be monitored to ensure a build-up does not occur. Oil and grease can be particularly effective at decreasing the wettability of a soil and ultimately preventing irrigation. The use of surfactants can potentially overcome this problem where it is an issue.

Human health concerns focus on bacterial considerations and treatment processes must be chosen with this in mind. While rain water will probably not need treatment other water sources will. It is best to work within the Australia Guidelines for Water Recycling as this document clearly outlines strategies for reduction of potential health impacts. Along with treatment there are protocols that are likely to be required with some water use. The protocols are aimed at preventing staff, users and the general public from potential pathogenic threats.

Animal and livestock health may also need to be considered where they may also utilize the ground. Importantly, pigs cannot be allowed on a field that is irrigated with recycled black water due to the threat from *Taenia solium* or pork measles. Other significant risks include *Taenia saginata* in cattle, *Mycobacterium paratuberculosis* in cattle and sheep and *Giardia lamblia* in cats and dogs. Ultimately responsible risk assessment should be performed following the Australian Guidelines where the protection of animal is required.

Perceptions of alternative water use are generally all favourable when it comes to sports field irrigation. Studies have placed acceptability of various waters to be use in the order of stormwater as most acceptable followed by recycled grey water, recycled black water and finally desalinated sea water. The reason for the low acceptability of desalinated seawater appears to be it energy consumption and associated greenhouse gas risk. Production of desalinated water using renewable energy sources may overcome some of this concern.

The six water sources investigated in detail were rain (roof) water, stormwater, grey water, black water, ground water and desalinated water.

In general only desalinated seawater is rainfall independent with grey water and black water recycling being largely rainfall independent (although it is dependent on incoming volumes that often decrease during water shortage) than the other three water sources. Ground water is highly dependent on natural recharge rates often making it unsustainable, however it can be particularly efficient when combined with aquifer recharge of another water source for longer term water storage. The volumes of water generated by rain water may be too low for use as an independent source, but would be suitable when supplemented by another water source.

In terms of contamination, salinity is a major issue in recycled grey and black waters, some ground waters and desalinated sea water. In these instances calcium addition may be required. These saline water sources should not be used on clay soils. Salinity can be reduced by treatments such as reverse osmosis, however these will be high in energy costs.

Metal contaminations are generally a problem in rain and storm water treatment. They are a function of the catchment and avoidance of copper or galvanised metals, particularly roofing can help reduce the impact. While treatment may not be necessary, monitoring the soil may be required where these are in high quantities.

Desalinated sea water may be potentially harmful in terms of its boron content, depending on the desalination technique used. Where this is a concern, clippings should be removed after mowing to ensure no build up of boron can occur.

The provision of nutrients is an important aspect of grey and black water recycling. A number of researchers have shown that recycled black water will provide all of a turf's phosphorus and potassium requirements and go a long way to meeting the nitrogen requirements. Grey water will perform similarly.

Finally, any considerations of alternative water must consider all local requirements and guidelines. This report is aimed at a Melbourne audience and therefore makes reference to various Victorian and Australian guidelines. It is important that any planning be considered from the point of view of the most current version of these guidelines that can be typically found online.

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CHAPTER 1 – Introduction

Water is a major global, national and local issue. While the water scarcity concerns of a few years ago are retreating from people's mind with increased rainfalls and the commissioning of new desalination plants along Australia's east coast, water will continue to be an issue for Australia. Growing population and the potential impacts of climate change particularly in the southeast corner of Australia. Recent restrictions in Victoria and Queensland and ongoing ground water concerns in Western Australia should serve as a warning to sports facilities managers of conditions that could easily occur again in the future.

It is understandable that when water scarcity becomes an issue, saving high quality water for drinking and domestic purposes would become a priority. The potential substitution of non-potable water in non-potable uses cannot be ignored. However the protection of turfgrass, particularly when used for sport is also important. Studies from the USA have shown the turfgrass in New Mexico is actually the second highest earning crop through membership fees of golf clubs [1]. A recent study in Australia has seen significant community support for local sports fields and tentatively placed the social worth of a sports field at $500,000 [2]. Coupled with the benefits of exercise and team sports [3], there is good reason to protect sports fields and ensure continued irrigation.

While potable water is protected, a range of water sources including rain water, storm water, grey water, recycled municipal water and brackish and sea waters would be potentially attractive alternative. The relative long-term reliability of some of these sources could be questionable. This is one argument for diversification of water sources to ensure continuing reliability.

There are other potential options for water reduction however. Connellan [4] has previously noted that water conservation in sports field irrigation should focus on the following:

- Selection of water efficient turf species
- Management of turf to maximise water use efficiency
- Selection of a well designed irrigation system
- Management of the irrigation system to maximise efficiency

To this can easily be added:

- Management of use of the field to minimise damage and wear

This work is part of a Smart Water funded project with the aim to assist sports ground managers in identifying suitable water reduction options and potable water replacements. In particular the aim was to re-focus thinking of water issues from a broader distributed environment to the local scale as shown in Figure 1.1. This highlights the potential use of water from local facilities such as toilets and clubhouses before looking further afield to sewer mining and decentralized (neighbourhood-sized) sewage treatment and reuse with centralized recycled water from large city-sized sewage treatment plants as the final option.

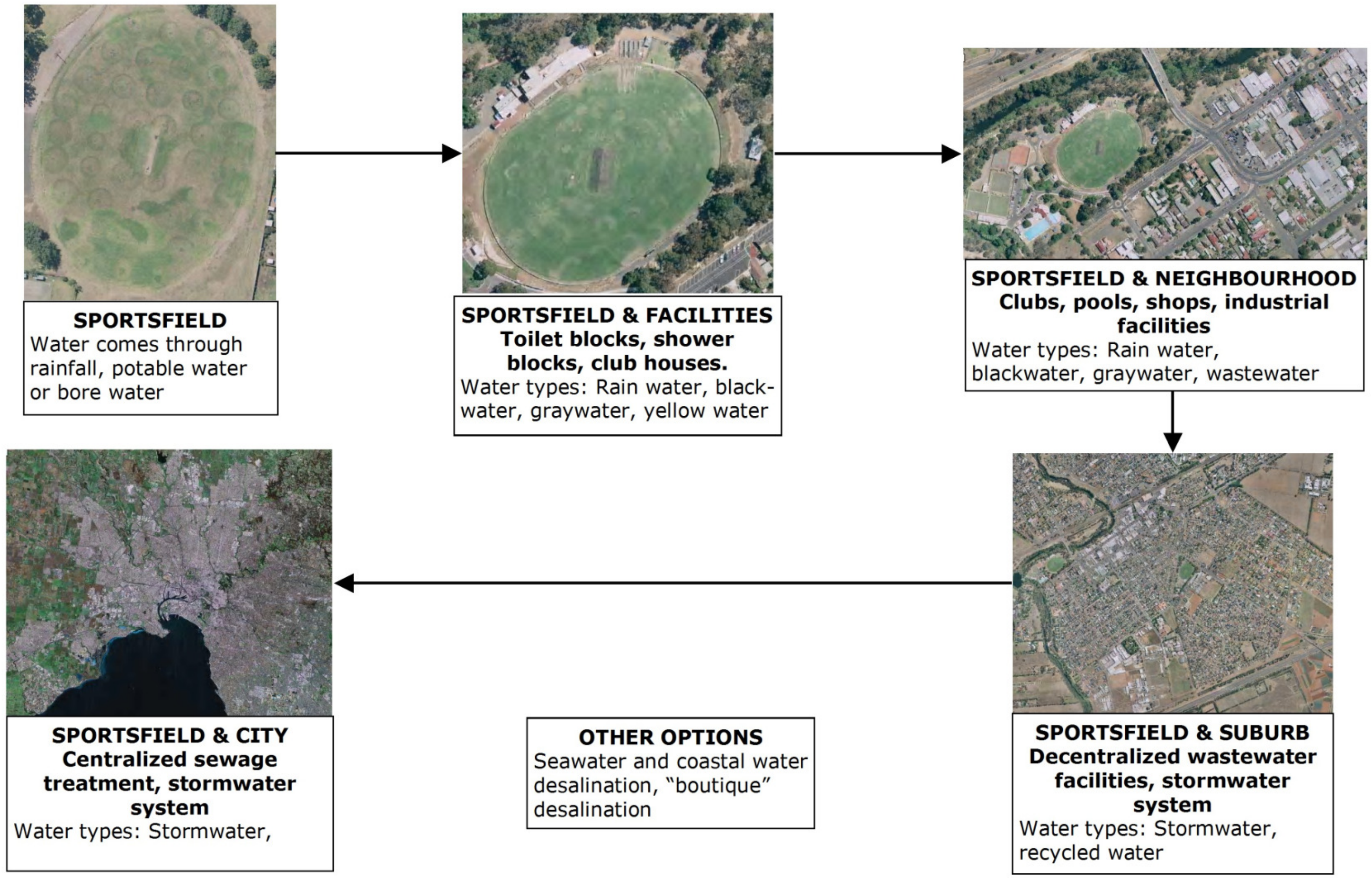

Figure 1.1 Potential water sources for sports fields based around different conceptions of the sports field's local environment.

The role of this document is to highlight potential concerns and address important issues with regards to some of the changes that can be made. These are partially of a technical nature, but will also address health and social concerns as well as the playability of sports on different turfs. It is hoped that the final product of this report will provide the backbone of an information package to sports ground managers when investigating more sustainable practices in water use.

Important Notes

The guidelines referenced throughout this document, particularly the various Australian Guidelines for Recycled Water [5-7] were current at the time of writing, but are always subject to review. Any decision maker should ensure that the most current guidelines and legislation will be followed for any proposed project.

It should be noted that while water qualities are presented here for a number of water sources, there is always variations with waters from the similar sources. While water qualities have been assessed generally, they should serve only as a rough guide.

Format of the Report

Chapter 2 of this report focuses on the changes that can be expected from changes in water turf and soil as well as general issues to do with irrigation water. This addresses concerns such as general turf properties, health, playability, acceptability and irrigation delivery and water storage. This provides the necessary background to assist the decision-making process.

Chapter 3 assesses different water sources and their potential for use in irrigation. As part of the project the following water sources were consider: roof water, storm water, grey water, black water, ground water, brackish water and sea water. Specifically each one considers major constituents, treatments and advantages and disadvantages to using the water.

CHAPTER 2 – General Issues

2.1 Turf and Soil Type

One of the more common methods currently chosen to reduce water usage in sports fields is to convert the turf species from a cool-season turf to a warm-season or artificial turf. While this can be effective at reducing water, there may be unintended side effects particularly with regards to playability and injury rates. The following sections are a general discussion of the differences between turf and soil types and the changes that can occur after transition from one type to another.

2.1.1 Cool-Season vs Warm-Season Turf

Selection of turf has typically been performed based around local climatic conditions, but with the focus on temperature rather than rainfall. In this respect cooler climates tend to rely on cool-season turfs that have adapted to temperatures in the range 15 to 24 °C, while warmer climates are better suited to warm-season turfs that are adapted to temperatures in the range 27 to 35 °C In recent times, due to the effects of drought, water restrictions and possible impacts of climate change, this strategy is being refocused towards water availability.

The main physical difference between warm- and cool-season turf is the direction in which the leaf grows. Cool-season typically grow in a vertical direction while warm-season tends to grow more horizontally [8] (note this is a generalization and there are exceptions [9]). This ultimately means that warm season turfs give greater shading for the soil and lower leaves and this helps to reduce the rate of evapotranspiration or water loss from the soil (either through use/transpiration by the turf or evaporation from the soil) [8]. Table 2.1 give the water use for seven turfgrasses over a 12 week period. It can quickly be seen there is a significant difference between warm- and cool-season turf species. Reduced evapotranspiration contributes to the lower irrigation requirements of warm-season turfs and the reason why there is a drive towards replacing cool-season turfs with warm-season varieties in Melbourne. Table 2.2 shows a list of typical warm- and cool-season turfs and some of their properties. It is not just the amount of water used or lost from the turf that is important to selection however, there are a range of other parameters that are important in this respect. These include:

- Drought tolerance – This is the ability of the turf to survive long periods with less water than is required. Typically warm-season turfs are more drought tolerant.
- Salinity tolerance – This is the ability of the turf to survive in a highly saline soil, or with a highly saline irrigation water. Typically warm-season turfs have greater salinity tolerance
- Wear tolerance – This is the ability of the turf to tolerate heavy traffic without showing signs of damage. Typically warm-season turfs have a greater wear tolerance [9].
- Recuperative potential – This is the ability for a turf to recover from damage to use and wear. It should be noted this is the potential and not the rate, recovery rates may vary between species that have the same recuperative potential.
- Heat tolerance – This is the ability of the turf to withstand sustained high temperatures. Typically warm-season turfs have greater heat tolerance.

Table 2.1. Water use over 12 weeks for seven turfgrass species. Adapted from [10]

Turf species	Water use over 12 weeks (L)	Transpiration Ratio (g Water/g Dry Matter)
Warm-season turfs		
Cynodon dactylon Couch	33.6	308
Paspalum distichum Seashore paspalum	36.1	343
Pennisetum clandestinium Kikuyu	40.1	346
Buchloë dactyloides Buffalograss	37.3	365
Zoysia japonica Japanese Lawngrass	33.7	420
Cool-season turfs		
Festuca arundinacea Tall fescue	55.9	586
Lolium perenne Perennial ryegrass	49.6	671

- Cold tolerance – This is the ability of the turf to withstand sustained low temperatures. Typically cool-season turfs have a greater cold tolerance.
- Frost tolerance – This is the ability of the turf to withstand frosts and ice. Cool-season turfs are typically more frost tolerant
- Mow tolerance – This is a measure of how well a turf will survive when mowed to a short height.
- Shade tolerance – This is the ability of a turf to survive with limited sunlight.
- Flood tolerance – This is a measure of the ability of a turf to withstand period where it is immersed in water.

Table 2.2 gives the tolerances of important turfgrass species. It should be noted that these are generalized descriptions and there can be significant variation within species [8].

One of the other main differences between warm- and cool-season turfs is their periods of dormancy. Warm-season turfs tend to be poorly tolerant of cold conditions, as noted previously, and enter a period of dormancy, typically over winter, as a way of avoiding these conditions. During dormancy pigment production ceases and the turf loses its green colour [9]. This leads to a brown or white coloured turf. The extent of discolouration varies between species with *Eremochloa ophiuroides* (centipedegrass) being one of the worst performers [9]. Table 2.3 give the general trends in terms of discolouration. Discolouration can be avoided through the application of turf colourants (chemicals that will re-establish turf colour) [9], applications of fertilizer (although this can be damaging to the turf, particularly over wet winters) [11] or else warm-season turfs can be overseeded by cool-season turfs [9]. This last option may be more appropriate due to dormancy also impacting on the wear tolerance and recuperative potential of some turfs [9]. There are hybrid turfs that have been developed specifically for colour retention over winter. These are typically couch hybrids (*Cynodon dactylon* x *Cynodon transvaalensis*) and one of the more successful species is Wintergreen.

Table 2.2: Common turfgrass species and their tolerances to different environments

Latin Name	Common Name	Warm or Cool Season	Tolerances											References
			Drought	Salt	pH	Wear	Recuperative Potential	Heat	Cold	Frost	Mow	Shade	Flood	
Agrostis canina	Velvet bentgrass	Cool	P	P	P			P			G	MG		[9, 12-14]
Agrostis capillaris	Colonial bentgrass, common bentgrass, Highland bentgrass	Cool	P	P	5.5-6.5	P	M	M	MG		MG	MG		[8, 9, 12-17]
Agrostis stolonifera	Creeping Bentgrass	Cool	P	MG	5.5-6.5	P	MG	M	G		G	M	G	[8, 9, 12, 13, 15-17]
Anoxopus affinis	Carpet grass	Warm	P	P	4.5-5.5	P	M	G	P		M	M		[8, 9, 12-14, 16]
Buchloë dactyloides	Buffalo grass	Warm	G	M				G	G		M	P	G	[9, 12-14, 16, 17]
Cynodon dactylon	Couch, bermudagrass	Warm	G	G	5.5-7.5	G	G	MG	P		MG	P	G	[8, 9, 12-17]
Cynodon transvaalensis	South African couch	Warm		G					M		MG			[13, 15, 17]
Digitaria didactyla	Blue couch, Queensland blue	Warm	G	MG	5.5-6.0	MG		MG	M	P				[8, 12]
Distichlis spicata	Saltgrass	Warm		G										[13, 16]
Eremochloa ophiuroides	Centipedegrass, Chinese lawn grass	Warm	P	P	5.0-6.0	P	P	G	P		M	M	P	[9, 12-14, 16, 17]
Festuca arundinacea	Tall fescue	Cool	MG	MG	4.7-8.5	MG	P	MG	M		P	G		[8, 9, 12-17]

P = Poor, M = Moderate, MG = Moderate to Good, G = Good

Table 2.2 cont: Common turfgrass species and their tolerances to different environments

Latin Name	Common Name	Warm or Cool Season	Tolerances											References
			Drought	Salt	pH	Wear	Recuperative Potential	Heat	Cold	Frost	Mow	Shade	Flood	
Festuca longifolia	Hard fescue	Cool	MG	P								G		[9, 14, 16]
Festuca rubra	Red fescue, Chewings fescue	Cool	MG	M	5.5-6.5	M	M	P	M		M	G	P	[8, 9, 12-17]
Lolium multiflorum	Annual ryegrass, Italian ryegrass	Cool	P	M	6.0-7.0			P	P		P			[9, 13, 15-17]
Lolium perenne	Perennial ryegrass	Cool	M	M		M	P	P	P		M	M	P	[8, 9, 13-17]
Paspalum notatum	Bahiagrass	Warm	G	P	6.5-7.5	MG	P		P		P	M		[9, 13, 14, 16, 17]
Paspalum vaginatum *Paspalum distichum*	Seashore paspalum, salt water couch	Warm	G	G		M		G	P		MG	MG		[8, 13-17]
Pennisetum clandestinium	Kikuyu	Warm	G	MG		G		MG						[8, 12, 13, 15, 16]

P = Poor, M = Moderate, MG = Moderate to Good, G = Good

Table 2.2 cont: Common turfgrass species and their tolerances to different environments

Latin Name	Common Name	Warm or Cool Season	Tolerances											References
			Drought	Salt	pH	Wear	Recuperative Potential	Heat	Cold	Frost	Mow	Shade	Flood	
Poa annua	Annual bluegrass, wintergrass	Cool		P	5.5-6.5			P	M		MG	G	P	[9, 13-17]
Poa pratensis	Kentucky bluegrass	Cool	M	P	6.0-7.0	M	MG	M	MG		M	M	M	[8, 9, 13, 14, 16, 17]
Poa trivialis	Rough bluegrass	Cool	P	P	6.0-7.0	P		P	G			MG	MG	[9, 13, 14, 16, 17]
Stenotaphrum secundatum	St Augustinegrass	Warm	M	G	6.5-7.5	M	MG	G	P		P	G		[8, 9, 13, 14, 16, 17]
Zoysia Japonica	Japanese lawn grass, zoysiagrass	Warm	G	MG	6.0-7.0	G	G	G	M		MG	MG	P	[8, 9, 13, 14, 16, 17]
Zoysia materella	Fine-leaf zoysiagrass, manila grass	Warm	G	G	6.0-7.0	G	G	G	P		MG	MG	P	[8, 9, 13, 14, 16, 17]

P = Poor, M = Moderate, MG = Moderate to Good, G = Good

Table 2.3: Rough ranking of colour loss of warm-season turfs during dormancy. Adapted from [8, 9, 18].

Most discolouration	*Eremochloa ophiuroides* (centipedegrass)
	Buchloë dactyloides (buffalograss)
	Stenotaphrum variegatum (Variegated St. Augustinegrass)
	Stenotaphrum secundatum (St. Augustinegrass)
	Paspalum notatum (bahiagrass)
	Pennisetum clandestinum (kikuyu)
	Cynodon dactylon (couch)
	Zoysia materella (manilagrass)
	Zoysia japonica (Japanese lawngrass)
	Cynodon dactylon x *Cynodon transvaalensis* (Tifway)
Least discolouration	*Paspalum vaginatum* (Seashore paspalum)

Cool-season turfs may go dormant over the summer months or under drought-stress [8]. However discoloration is generally not an issue. Some discoloration may occur over winter, however this is not as severe as warm-season turfs.

Growth periods for warm- and cool-season turfs also vary significantly. Warm-season grasses tend to grow during spring to early summer [8] and fertilization and access to water is important during these times. During summer growth will drop off somewhat and root growth is important in autumn prior to the turf becoming dormant. Cool-season turfs grow in the opposite way, with autumn and spring being the main growth periods with minimal growth over winter and many species going dormant over summer [8]. This in turn impacts on fertilization and water availability.

Other differences between warm- and cool-season turfs ultimately come done to impacts of gameplay and safety. These issues are discussed in Sections 2.1.4 and 2.1.6 respectively.

2.1.2 Artificial turfs

Due to scientific advances and increasing water scarceness there has been an increase in the use of artificial surfaces for sports fields. Third generation artificial turfs have significantly improved in terms of visual impact and playability. The turfs currently available consist of a perforated rubber base with the artificial blades attached. Over this, to hold the blades upright is a layer of sand followed by a layer of rubber granules. These granules are often made from recycled automotive tyres [19]. The granules can also be dispersed during play and apparently can get into the eyes, nose and mouths of players [19], though wetting prior to play would reduce this. The field would generally need to be re-levelled after play [19].

The use of artificial turf does not necessarily eliminate the need for water however. Solar heat is easily absorbed and where natural turfs can transpire (i.e. evaporate water) lowering the surface temperature, this is not possible in artificial turfs. Some experiments have shown the surface temperature to reach as high as 93 °C compared to an air temperature of 37 °C [20], although about 20 °C higher than natural turfs appear more common [19, 20]. This has two impacts, firstly it results in the dehydration of players using the surface and potentially increase in heat-based injury from contact with the surface. Secondly, it has the potential to increase the potential for injury due to increasing traction [21]. To overcome these issues water is generally applied to the surface of an artificial turf before play [19]. Irrigation has been shown to reduce the surface temperatures by approximately 10 °C [20].

The application of water and potential for rain also bring about a second issue in runoff. Typically water from an artificial turf should be collected and undergo some basic treatment (e.g. detention) before release due to product that may leach from the artificial turf, specifically polyaromatic hydrocarbons and zinc from the rubber infill [22, 23]. The content of these compounds emitted is proportional to the age of the field [23], but in the early stages can be significant and the potential environmental impacts, particularly from zinc, must be considered [23, 24].

Potential health impacts and injuries associated artificial turfs are discussed in Section 2.1.6, however it is important to remember that minor injuries such as abrasions and burns do appear to be more significant on artificial turf while concussions appear less likely to occur [25]. This increased risk of largely insignificant injury has led to changes in player's attitudes and perceptions towards artificial turf. The only study to date to look at the impact of play in soccer has suggested that players take less risks and play a less aggressive game on artificial turfs than natural turfs [26]. Specifically they are less likely to use a sliding tackle due to the injuries they may sustain. This in turn impacts player perceptions of a game played on artificial turfs, with respondents to a survey suggesting that games played on artificial surfaces are worse than on natural turfs [26] though this is not necessarily the case. Importantly, the study found that players that regularly use an artificial surface adapt their game play to that surface and the impacts in these cases can be fairly insignificant [26].

One final impact of artificial turfs on game play comes from the cushioning effect of the rubber infill. Where a natural surface is quite hard, artificial surfaces are not an absorb some of the energy used in running. While this was not found to affect the speeds players achieved on the surface [26], it did result in players working harder to achieve the same results and tiring quicker [27].

2.1.3 Soil

The soil that makes up the root zone will also influence water requirements. Soil is a matrix of particles and aggregates of different size [28]. As the particles cannot pack intimately close to one another, there are gaps and channels between them that are generally referred to as pores. The size of these pores varies depending on soil properties. Large particles like sand tend to have very large pore spaces while small particles like clay have very fine pores. Clays can, however, aggregate. In doing this smaller particles cling together to form larger particles. This leaves large pores between the aggregates while small pores exist within the aggregates [28]. This is particularly useful in soil for turf.

Table 2.4 Recommended maximum rate of irrigation for various soil classifications. Adapted from [3]

Soil Type	Application Rate ($L.hr^{-1}.m^{-2}$)
Coarse sandy soil	50
Coarse sandy surface/compacted subsoil	44
Light sandy loam	44
Light sandy loam surface/compacted subsurface	31
Silty loam/compacted subsoil	15
Heavy textured clay	5

Different soils have different percolation rates and capacity to hold water. This is related to the pore size. In general, large pores increase the percolation rate, while small pores assist in the retention of moisture [28]. While sandy soils have high percolation rates, they have poor soil retention qualities. Well-structured aggregated clay on the other hand have both good percolation properties and good soil moisture retention [28]. While the level of water retention will determine how much water is available for use, percolation rates will limit the maximum irrigation rate. Table 2.4 shows the recommended maximum rates for irrigation of a range of soils.

In general for a turf to grow a soil pores sizes in excess of 0.1 mm are required [28]. This is due to the size of the root and its ability to work its way through a soil as well as having sufficient water and oxygen for growth. Fine soils, such as lake and flood plain sediments are not suited for sport fields due to the smaller pore size resulting in poor percolation and poor root growth [28].

Classifications of soils are based around the distribution of particle sizes within the soil. Based on their size, particles are classified as either clay (<2 μ), silt (2-20 μ) or sand (20-2000 μ) [29]. From these definitions it is possible to classify a soil texture using the triangular graph found in [29]

There are two main soil moisture definitions that are important in irrigation. The first is the field capacity. This is the amount of moisture retained in a soil after the excess has drained away after irrigation or rainfall [28]. Ultimately this is the maximum amount of water that can be retained by a soil. Table 2.5 gives the field capacity for different classifications of soil. The second important definition is the permanent wilting point. This is the soil moisture content from which the turf will stop extracting water. This ultimately is the driest a soil should become prior to irrigation [28]. Typical ranges for the permanent wilting point of various soils are also shown in Table 2.5.

Table 2.5 Field capacities and permanent wilting points for various soil types. Adapted from [30]

Soil Texture Class	Field Capacity ($cm^3.cm^{-3}$)	Permanent Wilting Point ($cm^3.cm^{-3}$)
Sand	0.07 – 0.17	0.02 – 0.07
Loamy Sand	0.11 – 0.19	0.03 – 0.10
Sandy Loam	0.18 – 0.28	0.06 – 0.16
Loam	0.20 – 0.30	0.07 – 0.17
Silt Loam	0.22 – 0.36	0.09 – 0.21
Silt	0.28 – 0.36	0.12 – 0.22
Silty Clay Loam	0.30 – 0.37	0.17 – 0.24
Silty Clay	0.30 – 0.42	0.17 – 0.29
Clay	0.32 – 0.40	0.20 – 0.24

2.1.4 Requirements of Surfaces for Sports

The physical requirements of turf or other surfaces for various sports have been investigated for about thirty years, but with the rise in artificial turf usage over the last decade, guidelines or regulations for each sporting authority have only recently been released. Table 2.6 outlines the current requirements for each sport. In the scientific literature, the focus has been on characterising existing systems or investigating artificial turfs. In general this means there is significant research on cool-season turfs, with minimal work on warm-season turfs. The following sections summarize the current state of knowledge.

2.1.4.1 Ball Bounce Resilience

Ball bounce resilience is defined as the ratio of the height a ball bounces compared to the height dropped [31]. It is particularly important to sports such as cricket, tennis and the football codes. Table 2.7 shows recommendations for ball bounce resilience from the scientific literature. While it is somewhat dependent on turf type and turf quality the ball bounce resilience is significantly influenced by soil type [31]. Studies by Canaway [32, 33] have shown that heavy soils give higher ball bounce resilience than sand under normal conditions while the reverse occurs during and after wear. This was attributed to the pooling of rainwater due to poorer infiltration of the soil by water during rain events. This in turn significantly reduces the ball bounce resilience. Though it is not as significant a factor, increasing mowing height was shown to decrease the ball bounce resilience, as was increased plant biomass [34]. Table 2.8 gives the ball bounce resilience for a range of turfs and soils.

Table 2.6 Turfgrass quality requirements as defined by sporting authorities

Characteristic	Test	Rugby Union [35]	Hockey [36]	Soccer (1 Star) [37]	Soccer (2 Star) [37]	Aussie Rules [38]	Cricket [38]
Vertical Ball Rebound		30-50%	5-20%	0.6-0.85m	0.6-1m	30-50%	5-20%
Angled Ball Behaviour		50-70% at 50 km/h with an impact angle of 25°		45-60%	45-70%	45-70%	35-60%
Traction	IRB Method	30-50 Nm				25-50 Nm	15-25 Nm spikes, 7-15 Nm
Energy Restitution		30-50%					
Base permeability	EN12616	> 180 mm/h	> 150 mm/h	180	180		
Ball Roll			5 - 15 m	4-8m	4-10m		
Ball to Surface Friction			>= 0.5 static, >= 0.35 dynamic				
Underfoot Friction			0.6 - 1.0				
Force Reduction			40-65%	60-70%	55-70%		
Linear Friction - Stud Deceleration				3-5.5 g	3-6 g		
Linear Friction - Stud Slide				130-210	120-220		
Rotational Resistance				30-45 Nm	25-50 Nm		

Table 2.7 Recommendations for ball bounce resilience. Adapted from [31]

Sport	Recommended Ball Bounce Resilience (%)
Soccer	20 – 45 25 – 38 20 – 50
Hockey	20 – 40 8 – 12
Tennis	25 – 36
Cricket	20 – 34 12 – 19

Table 2.8 Ball bounce resistance on different turfs and soils.

Species	Soil	Ball Bounce Resilience (%)	Ref.
Bare ground	Clay	41.4	[31]
Poa annua (Annual bluegrass)	Sand	29.5	[32]
	Soil	28.3	[32]
Lolium perenne (Perennial ryegrass)	Sand	34.4	[32]
	Soil	33.4	[32]
Poa pratensis (Kentucky bluegrass)	Sand	33	[32]
	Soil	30.5	[32]
	Clay	30.9	[31]
Festuca arundinacea (Tall fescue)	Sand	34.7	[32]
	Soil	36.5	[32]
Agrostis castellana (Browntop bentgrass)	Sand	31.4	[32]
	Soil	31.9	[32]
Agrostis stolonifera (creeping bentgrass)	Clay	30.7	[31]
Festuca rubra (Chewing's fescue)	Sand	35.2	[32]
	Soil	35.8	[32]
Festuca rubra (Red fescue)	Sand	35.8	[32]
	Soil	36	[32]
	Clay	37	[31]

2.1.4.2 Rolling resistance.

The rolling resistance of the turf is ultimately the deceleration that the ball experiences. It is defined as the distance the ball will roll across the surface before either stopping or losing a certain proportion of its speed [31]. It is essentially a measure of the speed of the turf and is important in sports such as golf, bowls, cricket, hockey and soccer. There are a number of techniques to measure ball roll, but an important specification is that the ball roll from a height of 1 m down a 45° incline [31]. The US Golf Association uses a slightly different instrument called a 'stimpmeter' [31]. Bowls greens also use a different technique, although the reproducibility is questionable [31]. When comparing data on rolling resistance it is important to keep these differences in mind.

Table 2.8 Bowls green speed (in s) for different turfgrass species. Adapted from [39].

Species	Dry	Wet
Festuca rubra ssp. *litoralis* (Slender red fescue)	11.5	11.5
Festuca rubra ssp. *commutata* (Chewing's fescue)	10.9	10.8
Agrostis capillaris (Colonial bentgrass)	10.9	10.7
Agrostis castellana (Browntop bentgrass)	11.2	10.9
Poa annua (Annual bluegrass)	10.5	10.2

Table 2.9. Golf green roll distance (in m) for different turfgrass species. Adapted from [39]

Species	Dry	Wet
Festuca rubra ssp. *Litoralis* (Slender red fescue)	2.21	1.90
Festuca rubra ssp. *commutata* (Chewing's fescue)	2.10	1.82
Agrostis capillaris (Colonial bentgrass)	2.10	1.80
Agrostis castellana (Browntop bentgrass)	2.09	1.80
Poa annua (Annual bluegrass)	1.72	1.51

Rolling resistance can be influenced by a number of factors. As would be expected taller grass (higher mowing height) results in lesser roll [40]. While mowing height is important, surface moisture also has a role to play, with wetter soils resulting in lesser roll [40]. This would in turn imply that during periods of rain more pervious soils will perform better under this parameter.

The effect of turf species is reasonably well defined [39]. Tables 2.8 and 2.9 give the ball roll resistance for different bowls greens and golf greens. It should be noted that although this data came from the same study, the measurement techniques were different. Overall, however, this studied showed the best performance was with *Festuca rubra* spp. *litoralis* (Slender red fuescue) [39]. An investigation of *Cynodon* species has given roll distances greater than those reported in Table 2.9, typically in the range 2.34 to 2.94 m [41]. This may be due to differences in the ball roll test used however, although the authors claim the coefficient of friction is similar to that seen for *Agrostis stolonifera*. Importantly, the only difference within the *Cynodon* species was an apparent decrease in the ball roll distance for South African couch (*Cynodon transvaalensis*).

2.1.4.3 Friction and Spin

While this property is very important to a turf surface, it is poorly understood. It is essentially responsible for variations in speed, direction and ball rotation during ball-surface contact. This is partially because it is difficult to define scientifically and this leads to significant variation in the experiments that have been performed, though they typically focus on what leads to friction and spin [31]. Consequently there has been no significant work published on this property and its variation between different turfs.

2.1.4.4 Shoe-Surface Traction

Shoe-surface traction defined the grip of the shoe on a surface. While it may be an injury risk (see Section 2.1.6), it is generally considered desirable to ensure best player performance [21]. Ranges of "normal" traction ranges for Australian Football League fields are shown in Table 2.11. In the unacceptably low range players are likely to slip and the pace of the game slows, while in the unacceptably high range, the surface holds too well and places significant stress on joints during pace and direction changes.

Measurement techniques for traction can vary, but a selection of studies by Canaway [31-34] have established an apparatus to test the traction using a studded disc that closely mimics the studs used in sports shoes. Table 2.12 shows the results of a range of turf species and soil types. Traction values have also been determined for warm-season species, while these are not directly comparable because of slight differences in measuring technique, the ultimate source of resistance is similar and the values are in a similar. These values are shown in Table 2.13.

Table 2.11 Acceptability of different traction values in AFL. Adapted from [42].

Performance Indicator	Traction (Nm)
Unacceptably low	< 20
Low normal	21 – 39
Preferred Range	40 – 55
High normal	55 – 74
Unacceptably high	> 75

Table 2.12 Traction for different turf species on different soils.

Species	Soil	Traction (Nm)	Reference
Poa annua (Annual bluegrass)	Sand	55	[34]
	Soil	52	[34]
Lolium perenne (Perennial ryegrass)	Sand	72	[34]
	Soil	66	[34]
	Unspecified	66	[33]
Poa pratensis (Kentucky bluegrass)	Sand	72	[34]
	Soil	70	[34]
	Unspecified	77.6	[33]
Festuca arundinacea (Tall fescue)	Sand	69	[34]
	Soil	64	[34]
Agrostis castellana (Browntop bentgrass)	Sand	66	[34]
	Soil	57	[34]
Agrostis tenuis (Highland bentgrass)	Unspecified	58.4	[33]
Festuca rubra (Chewing's fescue)	Sand	77	[34]
	Soil	68	[34]
Festuca rubra (Red fescue)	Sand	74	[34]
	Soil	71	[34]
Festuca rubra (Highlight)	Unspecified	55	[33]

Table 2.13 Average traction on warm-season turfs. Adapted from [43]

Turf Species	Average peak torsion (Nm)
Vegetative Bermudagrass (*Cynodon dactylon*)	75.5
Seeded Bermudagrass (excluding "Princess" and Riviera") (*Cynodon dactylon*)	66.4
Densely Seeded Bermudagrass - "Princess" and "Riviera" (*Cynodon dactlyon*)	76.7
Hybrid Bermudagrass (*Cynodon dactylon* x *transvaalensis*)	75.3
Queensland blue couch (*Digitaria didactyla*)	69.6
Swazigrass (*Digitaria didactyla*)	82.3
Seashore Paspalum (*Paspalum vaginatum*)	64.9
Kikuyugrass (*Pennisetum clandestinum*)	55.7
St Augustinegrass (*Stenotaphrum secundatum*)	61.8
Marine Couch (*Sporobolus virginicus*)	48.9
Japanese lawngrass (*Zoysia japonica*)	65.1
Manilagrass (*Zoysia matrella*)	60.2

2.1.4.5 Surface Hardness

Surface hardness is important primarily from the point of view of safety (see Section 2.1.6). However it also impacts on the endurance of players during a match and its speed [21]. While surfaces that are too hard can result in injuries to players, soft surfaces are more elastic and absorb more energy from players during running. This in turn means players are required to do more work for the same results and ultimately tire quicker. This is one of the significant differences that has been seen by both researchers and sportsmen with third generation artificial turfs [27, 44]. Here the rubber infill gives a significant cushioning effect and causes players to work harder and tire quicker than on natural turf surfaces [25]. Ultimately a good balance of safety and playability is required when aiming for a specific surface hardness.

Surface hardness is primarily a factor of the underlying soil [21], however the cushioning effect provided by some turfs can provide for some more subtle differences. A more thorough discussion is provided in Section 2.1.6.

2.1.5 Management of Sports Turfs for Drought and Long Dry Spells

2.1.5.1 Management Practices

Mowing

There are a number of different viewpoints on how to use mowing height to reduce the irrigation requirement of a field. Differences largely come about from the whether it is a long-term or short-term view. Over the long-term, it is generally recommended that mowing occur at the highest height allowed by the turf and users [4]. This allows the roots to grow longer and ultimately gives the turf a greater drought resistance [45]. Once a drought or water-shortage has descended on the field, the mowing height can be reduced. This will decrease the surface area of the leaves and give a short-term decrease in evapotranspiration [8]. It should be noted however that this is more efficient for cool-season turfs than warm-season [10]. This is due to the more horizontal nature of leaves in warm-season turfs generally providing shading of the soil and lower leaves [8]. Lower mowing heights ultimately only exposes lower leaves that previously had not been transpiring at high rate.

Mowing frequency also impacts on water use, with increased frequency increasing damage and therefore growth of the turf [8]. In drought conditions it is best to reduce the mowing frequency where possible.

Fertilizer Use

The use of fertilizer encourages growth. This growth requires water and consequently the evapotranspiration of a turf increases with fertilizer use [46]. Where it is feasible fertilizer use should be reduced or avoided altogether in order to reduce irrigation requirements. Alternatively, organic fertilizers can be employed that release nitrogen at a slower rate reducing water requirements [3].

Other Practices

Other practices that can be useful in reducing water requirements include:

- Removal of thatch will improve water penetration to the soil and irrigation efficiency [8].
- Aeration of turf should occur to reduce surface compaction and improve percolation of water into the turf. Recommendations suggest this should occur prior to irrigation or rainfall [3].

Finally, it will also be important for turf managers to consider how changing practices and more intensive use will impact on turf wear. Often during water shortage activities will be concentrated onto specific fields due to the water restrictions. Consequently the following practices should be considered:

- Restrict training and pre-season matches to non-essential fields [3]
- Relocation of centreline and goal box in football to reduce wear in these areas [3]
- Widening of the wicket table in pitch based sports to wear in this area [3]

2.1.5.2 User Practices

There are a range of practices that can be adopted by users to reduce the effect of wear and damage to a turf when it is under reduced irrigation conditions. These include:

- Transfer fitness and skills training off match or turf surfaces [3]
- Reduce playing time or shorten the season [3].
- For warm-season turfs consider altering the sporting season from a winter sport to a summer sport [3]
- Rotate training areas when on the field [3]
- Don’t use studs on fields [3]

2.1.6 Sporting Injury, Health and Turf

2.1.6.1 Introduction

Injury is generally the most significant concern managers have when changing a turf from one form to another. Understanding what can cause injury and what the main differences could be is important when making a decision to change turf type. The following section is a discussion of the properties of turf that increase injury rates as well as the current state of the knowledge with regards to injury comparison between warm- and cool-season turfs and natural and artificial turfs.

2.1.6.2 Properties that Cause Injury

A very thorough review of sports injuries has recently been performed by Chivers and Orchard [21]. They felt there is little work to connect ground conditions to injury and that the studies generally performed rely heavily on perceptions. However, they were able to identify environmental hazards at sporting grounds that relate to injury. These include:

- Uncovered hazards such as sprinkler heads or cricket pitches
- Uneven surfaces
- Debris, rubbish and rubble
- Type of surface (natural vs synthetic, clay vs sand)
- Poor turf coverage
- Type of grass
- Surface hardness (inversely proportional to soil moisture content [21])
- Surface traction (correlated to the amount and type of grass cover [21])
- Weather conditions

In general the hardness and traction are probably most significant as other issues, such as the type of surface, type of grass and weather conditions are related back to these two properties.

<u>Early-Season Bias and Hardness</u>

Injuries that are related to ground conditions are generally associated with the lower extremities – legs, ankle, knees etc [21]. Most studies focus on these type of injuries, in particular the ACL (Anterior Cruciate Ligament). Early studies into ground conditions and injury focused on the phenomenon of early-season bias in sports injuries and most of the available literature deals with this issue. Early-season bias refers to the increased rate of injury seen in some sports at the start of a season. Researchers typically associate it with ground hardness as the sports it is associated with are played during winter when rainfall increases and evaporation decreases making a surface softer [21]. Evidence for this is cited in the results of a study of American football where early-season bias was only seen in open air fields, not indoor stadiums [21] and that American soccer, a summer sport, shows a late season bias that would be associated with increasing hardness as a surface dries out [47]. There is some controversy with this however as not all sports show the same trends. While early-season bias is reported in rugby union [48], American football, European soccer, Australian rugby league and Aussie Rules football did not show a statistically significant early-season bias [21, 49, 50] and Gaelic football instead saw a late-season bias [21]. There is also the possibility that early-season bias is due to the fitness level of the players as they start a new season. Importantly, Orchard [49] has shown a significant trend towards softer grounds that is accompanied by increased injury, but statistically the two could not be related. The conclusions were that while surface hardness may play a role, other factors, particularly traction may be more significant.

Other studies have however identified hardness being related to injury in other ways. A study of the AFL has shown that weather conditions are significantly associated with injury risk [49]. In particular conditions of high evaporation for one month prior to the match and low rainfall for the previous year were associated with higher injury risk. An AFL study has also argued that greater hardness led to faster games being played on the surface, lowering cushioning properties and increasing collision impact forces [21].

Traction

The importance of traction to sport injury is starting to receive significant attention, with a number of researchers now highlighting it as having a major effect on injury risk. This particularly refers to the surface-shoe interaction. A study in soccer [51] has shown that high friction leads to the sportsman increasing loads associated with twisting and turning during play. This, in turn, increases the injury rate. While surface hardness is related to moisture and rainfall, causes for changes in traction are more difficult to identify, with the obvious exception of high rainfall. Traction in general is related to the type of turf cover and the extent of this cover. Studies have shown that traction shows a slow, constant decline over a playing season [21]. Traction is also related to the mowing height, with shorter cut grass giving higher traction values [52]. While high traction may be a contributor to high injury risk, it is also highly desirable by sports participants and some balance needs to be struck. Shoes used in most winter sports tend to increase traction regardless of the surface type. While the type of surface may be a factor, the design and manufacture of shoes may play a greater role in overcoming these issues than turf choice [53].

2.1.6.3 Turf Type

Natural Turf

While grass type, in particular its relationship to surface-shoe traction, is believed to play a role in injury risk, there is very little work investigating this as a variable. However, an Australian AFL study has drawn the conclusion that the cool-season grass perennial ryegrass has lower traction and is associated with lesser injury risk than the warm-season turf couchgrass (bermudagrass) [49]. Similarly Kentucky bluegrass has been shown to have higher traction than ryegrass and red fescue [52] and it is assumed will be associated with greater injury risk as a result [48]. Result of studies into the shoe-surface traction of various warm-season turfs are shown in Table 2.13 [43]. General hypotheses about the effect of grass type on injury essentially consider the root density, lower root and shoot density will lead to lower shoe-surface traction [8]. Mowing height also plays a role in that greater mowing height gives greater cushioning effect and therefore lesser injury risk [48]. Also traction has been found to increase as the mowing height decreases.

Artificial Turfs

Research into injury risk on artificial turfs as opposed to natural turfs has shown varied and sometimes contradictory results. This is due to the development of artificial turfs from first generation Astroturf to the current third generation on which studies are just starting to appear. The focus of this discussion will be on third generation artificial turfs (the most likely to be installed now) and their impacts on injury rates and health.

Artificial turfs typically exhibit a higher traction than natural turf [4] and it would be anticipated that a greater number of injuries would result. A large number of studies however have not been able to conclusively show this with any difference between artificial and synthetic not being statistically significant [54-58]. However, when a breakdown of injury type is considered there is some variation witnessed. Foot and ankle injuries have been found to be more common on artificial turf [54, 59]. Knee injuries are typically considered only slightly more common on artificial turfs than natural [54, 58]. These results are complimented by the study of Nigg and Segesser [60] who found that while non-serious injury is more common on artificial turfs, serious injuries occurred just as frequently. In terms of non-serious injury, abrasions and burns are reported as being typical and often missed in studies as they do not result in lost time [25]. While these injuries are only of minor concern the potential for infection is quite important. A study of American football players has shown a link between *Staphylococcus aureus* infection and artificial turf burns with all abscesses forming at burn sites [61]. A further study was able to show that players that experienced abrasions on artificial turf were seven times more likely to suffer an infection than those who acquired their injuries on natural turf [62]. Despite these observations however, it is still not certain how the infections are transmitted or why the response on artificial turf is higher, although one suggestion has been that soil microbes that help to decompose saliva, blood etc are not present in artificial turfs [19].

Another important distinction is with concussions. Most recent studies have shown that concussions resulting from head to surface collisions are less common on artificial surfaces than natural surfaces [57]. This has been related to the extra cushioning effect provided by the rubber infill used on artificial turfs [25] and is one of their primary benefits.

The rubber infill while beneficial against injury, is also the cause for some concern with regards to health impacts. The infill, and the turf itself, can release volatile components as gases above the playing surfaces and be raised as fine dusts during sliding and tackling [19]. These components are inhaled by players and have led to serious concerns, particularly with respect to their cancer causing potential. The concern was so great that in 2008 a number of state legislators in New Jersey, New York and Minnesota have called for a moratorium to be placed on the installation of artificial fields using recycled tyres as infill until further studies can be performed [63]. There is also a strong grassroots movement in New York against the installation of further artificial turfs [64]. The major concerns here are with children being exposed to the chemicals as fields and open spaces typically reserved for children are more likely to be replaced as a cost cutting measure. A US EPA study however has suggested that the concentrations of harmful compounds from infill were below dangerous levels and studies of the bioaccessibility have suggested that there is no significant uptake when compared to other sources [23, 63].

2.2 Irrigation Water

2.2.1 Introduction

The impacts of water for irrigation are numerous. One of the most import concepts to understand however is the how to determine how much water to use or when and how to add water. Signs of over-irrigation commonly generate complaints [65] and will be even more significant during times of water shortage. The first part of this section looks at irrigation modelling and the sensors and irrigation systems that exist that can help to decrease water use and ensure over-irrigation does not occur.

Of equal importance is the effect of different irrigation water qualities on turf and soil. This is important when considering diversifying water sources to ensure that the water under consideration will not adversely impact on the play and quality of the turf.

2.2.2 Irrigation Volumes

2.2.2.1 Irrigation Modelling using Climatic Data

Irrigation modelling is important in understanding the requirements for a turf under relatively realistic conditions. Water requirements can be estimated in a number of ways the most basic being to subtract the rainfall for a site from the evaporation and assume what remains is required as irrigation. This technique is a fairly poor estimate of water requirements and is not particularly realistic. A more accurate way would be to consider model water requirements on a daily basis based on previous years' data. The way of doing this is pictorially described in Figure 2.1. Ultimately, the soil acts as a reservoir of water that is available to the turf. Rainfall will fill this reservoir until it is full and overflow will occur, either as runoff or through percolation of the soil. The reservoir will be depleted through use in the form of evapotranspiration (i.e. transpiration (or use) by the turf in growth and evaporation from the soil). When the reservoir is depleted, extra water must be added in the form of irrigation. The size of the reservoir is dependent on the soil type and the type of growth required [4]. The evapotranspiration is dependent on the turf type and the type of growth required (or available moisture) [4]. The ratio of percolation to runoff is also dependent on soil type, but this is not particularly important when calculating irrigation requirements.

The following section will provide a mathematical explanation of irrigation modelling techniques.

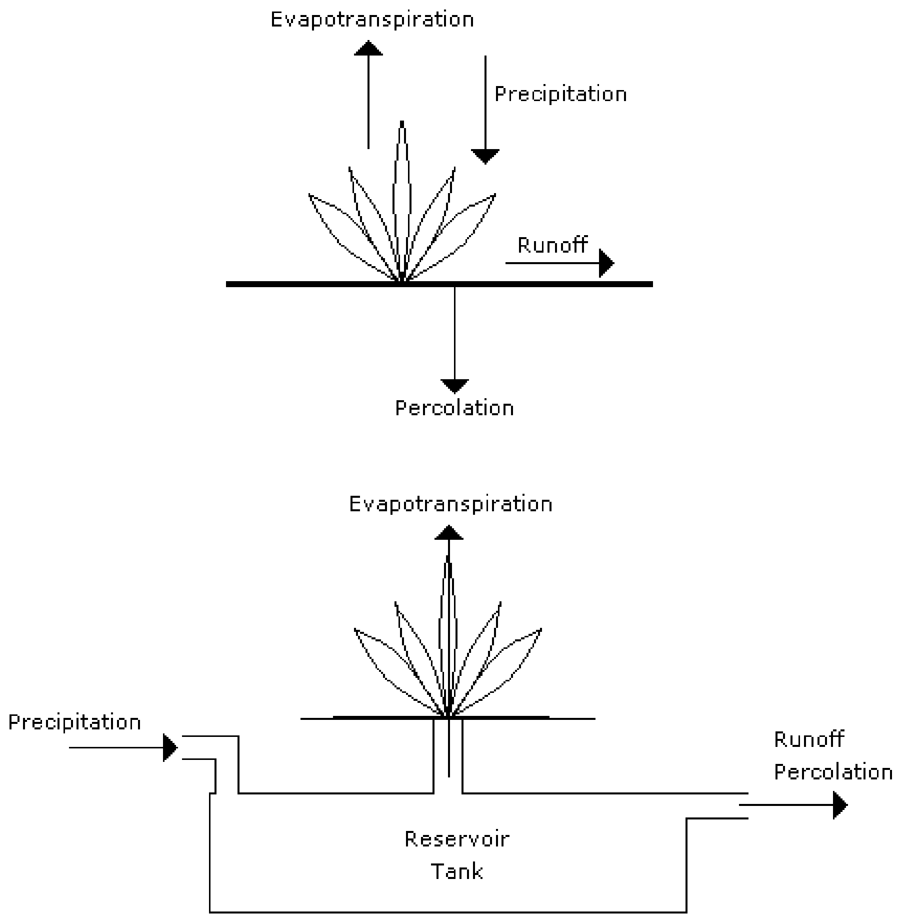

Figure 2.1 Basic illustration of water balance in turf management: Descriptive model (above) and engineering model (below)

Step 1 – Soil Water Retention

Determination of the ability of a soil to hold water is important to understanding the size of the irrigation reservoir. This is dependent on two factors: (i) the soil type and (ii) the root zone depth. The volume of water that can be depleted before irrigation is required is given by the equation:

$$V_{SM,C} = R_s \times d_{rz} \qquad \text{E-1}$$

where $V_{SM,C}$ is soil's moisture capacity, R_s is the soil retention factor and d_{rz} is the depth of the root zone. Table <?> shows the soil retention factors for typical soil types for different turf growth rates. The turf growth rates are important as they are determined by the amount of available water in a turf. High growth will be seen where significant water is available. Consequently the reservoir size for these soils is smaller as irrigation should be triggered more regularly. Turfs that can have a lower growth rate have larger reservoirs as the soil moisture content can be more heavily depleted. This results in less frequent but larger irrigations.

The rootzone for a turf is affected by a number of properties including irrigation frequency, frequency of fertilizer application and mowing height. In general for turfs the rootzone depth is assumed to be on the order of 30 to 40 cm.

Table 2.14 Allowable soil moisture depletion (in $mm.cm^{-1}$) for different soil textures under different growth regimes. Adapted from [8]

Soil Type	Vigorous Growth	Strong Growth	Good Growth	Little Growth	Minimum Growth
Sand	0.3	0.4	0.5	0.6	0.6
Loamy Sand	0.4	0.6	0.7	0.8	0.9
Sandy Loam	0.6	1.0	1.1	1.2	1.3
Loam	0.9	1.5	1.7	1.8	2.0
Poor Structured Clay	0.5	0.8	1.0	1.1	1.3
Good Structured Clay	0.7	1.1	1.3	1.6	1.9

Step 2 – Determining Evapotranspiration

Evapotranspiration (ET) can be calculated through two main of techniques: the pan evaporation model and the Penman-Monteith equation. The simplest of these is the pan evaporation model.

The Pan Evaporation Method

The ET in pan evaporation is defined by the equation:

$$ET_c = k_c E_P \qquad \text{E-2}$$

where ET_c is the actual ET, E_P is the evaporation from a flat water surface (or water pan) and k_c is the crop factor for the turf.

E_P evaporation data can be obtained from the Bureau of Meteorology. Within Melbourne there are three main sites measuring evaporation: Melbourne Airport, Melbourne Bureau of Meteorology Head Office and Latrobe University at Bundoora.

Crop factors are dependent on the turf type and the amount of growth required. The last of these is due to the fact that growth is dependent on water and greater growth will therefore use greater water. Table 2.15 shows the crop factors for warm- and cool-season turfs under different growth requirements. It is important that the growth selected at this point is the same as that selected for soil moisture as ET is also dependent on the amount of water available in the soil [66].

Table 2.15 Pan evaporation crop factors for warm- and cool-season turfs under different growth conditions. Adapted from [8].

Turf Type	Vigorous Growth	Strong Growth	Good Growth	Little Growth	Minimum Growth
Warm-season	0.7	0.55	0.5	0.425	0.25
Cool-season	0.85	0.775	0.725	0.7	0.65

Penman-Monteith Equation

The FAO Penman-Monteith equation is more complicated than the pan evaporation model, but does not require a knowledge of the local evaporation rate. It does, however, require knowledge of some more complicated meteorological concepts. All the required data is, however, available from the Bureau of Meteorology.

The ET by FAO Penman-Monteith is given by [67]:

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma\frac{900}{T+273}u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \qquad \textit{E-3}$$

Where ET_0 is the reference ET, Δ is the slope of the vapour pressure curve (kPa.°C^{-1}), R_n is the net radiation from the crop surface (MJ.m^{-2}.day^{-1}), G is the soil heat flux density (MJ.m^{-2}.day-1), γ is the psychrometric constant (kPa.°C^{-1}), T is the mean daily air temperature at 2 m height (°C), u_2 is the wind speed at 2 m height (m.s^{-1}), e_s is the saturation vapour pressure (kPa) and e_a is the actual vapour pressure (kPa).

The equation is essentially broken into two parts. The first part describes the water evaporated through solar radiation and heat applied to the ground, the second describes the equilibrium between water vapour (humidity) and water liquid above the grass and is a function the wind speed.

In order to calculate the data above, a significant amount of information is needed. The following discussion will break down how to calculate the individual components.

Psychrometric Constant (γ)

This is given by the equation [67]:

$$\gamma = \frac{c_P P}{\varepsilon\lambda} = 0.665 \times 10^{-3} P \qquad \textit{E-4}$$

Where P is the atmospheric pressure, c_P is the specific heat (1.013x10^{-3} MJ.kg^{-1}.°C^{-1}), ε is the ratio molecular weight of water vapour to dry air (0.622) and λ is the latent heat of vapourization (2.45 MJ.kg^{-1}).

Atmospheric pressure also needs to be calculated and can be found from the equation:

$$P = 101.3\left(\frac{293 - 0.0065z}{293}\right)^{5.26} \qquad \textit{E-5}$$

Where z is the elevation above sea level (m).

Air Temperature (T)

For this term, the average of maximum and minimum temperatures is sufficient. This data can be found from the Bureau of Meteorology.

Mean saturation vapour pressure (e_s)

The mean saturation vapour pressure can simply be taken as the average of the saturation vapour pressure at the minimum and maximum temperatures. Each of these can be found from the equation [67]:

$$e^0(T) = 0.6108e^{\left(\frac{17.27T}{T+237.3}\right)} \qquad \textit{E-6}$$

where T is the maximum or minimum temperature (°C).

Slope of the saturation vapour pressure curve (Δ)

The slope of the saturation vapour pressure curve is calculated using the mean temperature and the equation [67]:

$$\Delta = \frac{4098\left(0.6108e^{\left(\frac{17.27T}{T+237.3}\right)}\right)}{(T+237.3)^2} \qquad \text{E-7}$$

where T is the average temperature.

Actual vapour pressure (e_a)

The term can be calculated in a number of ways, however, for the Melbourne area calculation from relative humidity would be more appropriate due the relative ease with which it can be obtained from the Bureau of Meteorology. The equation is defined as:

$$e_a = \frac{RH_{mean}}{100}\left(\frac{e^0 T_{max} + e^0 T_{min}}{2}\right) \qquad \text{E-8}$$

Where RH_{mean} is the average relative humidity, T_{max} is the maximum temperature, and T_{min} is the minimum temperature.

Net Radiation (R_n)

The net radiation is a combination of the incoming shortwave radiation and the outgoing longwave radiation. It is given by the equation [67]:

$$R_n = R_{ns} - R_{nl} \qquad \text{E-9}$$

Where R_{ns} is the net shortwave radiation and Rnl is the net longwave radiation.

Net Shortwave Radiation (R_{ns})

The R_{ns} is given by [67]:

$$R_{ns} = (1-\alpha)R_s \qquad \text{E-10}$$

Where R_s is the solar radiation and α is the canopy reflection coefficient and can be taken as 0.23 [67].

Where solar radiation is not measured it can be calculated by [67]:

$$R_s = \left(a_s + b_s\frac{n}{N}\right)R_a \qquad \text{E-11}$$

Where n is the actual duration of sunshine (h, available from Bureau of Meteorology), N is the maximum possible duration of sunshine (h), Ra is the extraterrestrial radiation, a_s can be taken as 0.75 and b_s can be taken as $2 \times 10^{-5}z$ (where z is elevation above sea level).

The extraterrestrial radiation can be calculated by the equation [67]:

$$R_a = \frac{24\times60}{\pi}G_{sc}d_r(\omega_s \sin\varphi \sin\delta + \cos\varphi \cos\delta \sin\omega_s) \qquad \text{E-12}$$

Where G_{sc} is the solar constant (0.082 $MJ.m^{-2}.min^{-1}$), d_r is the inverse relative distance between the Earth and the sun, ω_s is the sunset hour angle (rad), ϕ is the latitude (rad) and δ is the solar decimation (rad). The latitude can be estimated as -0.6603 for Melbourne.

The inverse relative distance between the Earth and the sun is given by [67]:

$$d_r = 1 + 0.033 \cos\left(\frac{2\pi}{365} J\right) \quad \textit{E-13}$$

Where J is the day number (1= January 1^{st} and 365 = December 31^{st})

The solar declination is given by [67]:

$$\delta = 0.409 \sin\left(\frac{2\pi}{365} J - 1.39\right) \quad \textit{E-14}$$

The sunset hour angle is given by [67]:

$$\omega_s = \cos^{-1}(-\tan\varphi \tan\delta) \quad \textit{E-15}$$

Net Longwave Radiation (R_{nl})

The net longwave radiation is given by [67]:

$$R_{nl} = \sigma\left(\frac{T_{max}^4 + T_{min}^4}{2}\right)\left(0.34 - 0.14\sqrt{e_a}\right)\left(1.35\frac{R_s}{R_{so}} - 0.35\right) \quad \textit{E-16}$$

The temperatures in this case are given in Kelvin, σ is the Boltzmann constant (4.903×10^{-9} $MJ.K^{-4}.m^{-2}.day^{-1}$), e_a is the actual vapour pressure (calculated through equation *E-8*), R_s is the solar radiation ($MJ.m^{-2}.day^{-1}$) and R_{so} is the clear sky radiation ($MJ.m^{-2}.day^{-1}$).

The clear sky radiation is the solar radiation assuming there is no cloud cover. It can be approximated by the equation [67]:

$$R_{so} = (0.75 + 2 \times 10^{-5} z) R_a \quad \textit{E-17}$$

Where R_a is the extraterrestrial radiation (calculated from equation *E-12*) and z is the elevation above sea level (m).

Soil Heat Flux (G)

For daily calculations, this can be assumed as 0 [67].

Wind speed at two metres above ground level (u_2)

The wind speeds are generally calculated by the Bureau of Meteorology at a height of 10 m above ground level. To convert this to 2 m wind speeds the following equation can be used [67]:

$$u_2 = u_z \frac{4.87}{\ln(67.8z - 5.42)} \quad \textit{E-18}$$

Where u_z is the wind speed at a height above the ground of z (in m).

The evapotranspiration calculated using the FAO Penman-Monteith equation has been calculated for an artificial reference crop. This will need to be converted to evapotranspiration for the turf using the equation:

$$ET_c = K_c ET_0 \qquad \textit{E-19}$$

Where K_c is a crop coefficient, but does not take the same value as that for the pan evaporation method. In general the K_c values for warm-season turfs can be taken as 0.85, while that for cool-season turfs can be taken as 0.95 [67].

<u>Pan Evaporation vs. NAO Penman-Monteith</u>

Calculations have been performed for ET from a warm-season turf near Melbourne Airport, assuming its data. A comparison of the two estimations are shown in Figure 2.2. From here it is quickly obvious that the Penman-Monteith model is significantly higher in its ET prediction. This could simply be a function of the crop coefficients recommended and used as the same general trends are seen. It is important to understand, however, that the two cannot be used interchangeably.

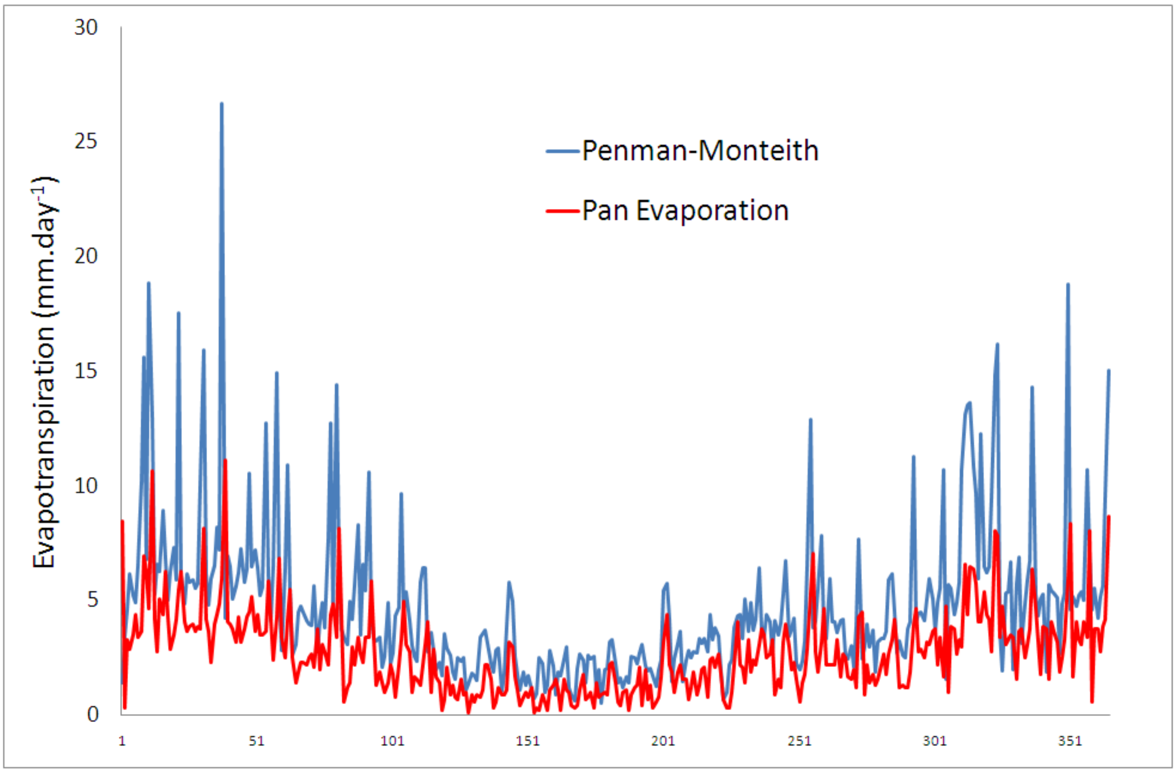

Figure 2.2 Comparison of Penman-Monteith calculations to the pan evaporation model for a field near Melbourne Airport.

Step 3 – Water Balance

With an understanding of the size of the reservoir, the inflow of water (rainfall, obtained from the Bureau of Meteorology) and the extraction of water (evapotransipiration), a simple water balance can be performed. For each day the following calculation is performed:

$$V_{SM} = V_{SM-1} + P - ETc - E_{SM} + I \qquad \text{E-20}$$

Where V_{SM} is the volume of available soil moisture, V_{SM-1} is the volume of available soil moisture the previous day, P is the precipitation, ET_c is the evapotranspiration calculated for that day, E_{SM} is the excess soil moisture and I is the irrigation depth. All values are give in mm. Excess soil moisture can be determined simply as the water in excess of the soil's storage capacity. Irrigation is determined to be equal to the amount required to saturate the soil (fill the reservoir) when the value for V_{SM} drops below zero.

The actual volume for irrigation can then be determined by taking the following equation:

$$V_{irr} = \frac{I \times A_{field} \times 10}{\varepsilon_{irr}} \qquad \text{E-21}$$

Where V_{irr} is the irrigation volume in kL, I is the irrigation depth in mm, A_{field} is the area of the field in ha and ε_{irr} is the irrigation efficiency. This is typically estimated as 0.75 [4]. However the Queensland Water Commission has estimated irrigation efficiencies for a range of irrigation types. These are shown in Table 2.16. The values should only be used as a guide to general trends however as there are significant differences within irrigation systems due to differences in user practices and uniformity.

By performing this calculation over an extensive period (at least one year, preferably more), an average annual irrigation requirement for a field can be determined that is more accurate than simple calculations based on annual rainfall and evaporation. It is also possible to determine daily requirements by updating this model based on daily ET and rainfall figures in order to estimate when irrigation may be required.

Table 2.16 The Queensland Water Commission guide to irrigation system efficiencies [68].

Irrigation System	Soil Type		
	Clay	Loam	Sand
Drip	0.95	0.95	0.95
Microspray	0.5	0.5	0.55
Spray – Day	0.5	0.5	0.6
Spray – Night	0.55	0.6	0.65
Sprinkler – Day	0.65	0.65	0.65
Sprinkler – Night	0.75	0.75	0.75

2.2.2.2 Soil Moisture Sensors

A more accurate determination of irrigation frequency can be determined by directly measuring the soil moisture content. Moisture sensors are mature technologies and a number of different measurement techniques can be found in commercially available technology [4]. The following techniques are commonly used:

- Neutron Gauges – This uses a radioactive isotope to generate neutrons for probing soils and is considered the most accurate method for determining soil moisture content [69]. The offset position of the calibration curve is significantly impacted by changes in soil composition (due to neutron interactions with individual isotopes) and must be calibrated to a soil before use [69]. The use of a radioactive source will place strict regulations on its sale and use, meaning it cannot be left unattended [69] and is probably unsuited for determination of irrigation scheduling on sportsfields.
- Water tension – Also known as soil water suction or soil water potential, this is a measure of the amount of energy with which water is held in a soil. It is measured using a water-filled tube with a ceramic tip on one end and a vacuum gauge on the other. The water in the tube comes to equilibrium with the surrounding soil and the pull on the water is measured by the vacuum gauge [70]. Measurements are generally dependent on soil type and the technique needs calibration [70].
- Dielectric properties – These are probably the more common of the commercially available soil moisture sensors [71]. Broadly they work around measuring variation in the soil dielectric constant [71]. This is a function of water content in the soil. There are two main types of dielectric sensors: Frequency Domain Reflectometers (FDR) and Time Domain Reflectometers (TDR) [71]. The main difference between the two is generally in their measurement technique. Their accuracy is generally considered to be good with one study showing that FDRs can be more accurate than neutron probes [69]. Capacitance-based sensors are easily automated [72]. Importantly they are not affected by salinity or temperature changes, but can be negatively impacted by bulk density changes due to soil compaction [73].
- Electrical resistance – These sensors use gypsum blocks with pores sizes roughly on the same scale as pores in the surrounding soil [69]. As such they are highly dependent on the soil type. The electrical resistance is measured and this is a function of water content. The technique is also sensitive to the salinity of the soil moisture as this impacts on the conductivity readings. The gypsum can also dissolve in high salinity water or in soils with a high moisture content [69]. Measurement error was found to be 20% or greater [69]. This can make them more erratic than dielectric sensors [74].
- Heat Dissipation – This sensor uses a similar gypsum block to electrical resistance measurements, but instead looks at the temperature rise due to applied heat [69]. It has been shown to be unaffected by the soil temperature, soil texture and salinity [69]. Though no claims have been made it is likely suffer from the same dissolution problems of the electrical resistance meters. One comparative study of soil moisture sensors found the results from the heat dissipation sensor to be the most erratic and unreliable of the sensors used [74]. It was acknowledged that this could have been a result of the nature of the tests however.

It is important that the installation of moisture sensors is performed correctly, as this can impact on the final effectiveness of the techniques. Some reports have shown that pockets of dry soil can leave sensors unresponsive to soil moisture changes [73]. Overall it must be remembered that, like any sampling technique, the choice of location of sensor is important in determining how representative it is of the overall turf conditions [4]. This can be somewhat overcome by using multiple sensors [75], however this comes with increased financial costs.

Calibration of sensors is also important, particularly as variations in soil-type can bring very significant differences in response [70, 74]. Having said this a recent study has shown the "out of the box," uncalibrated sensors can still give responses that are consistent enough for irrigation scheduling, despite the fact the actual values themselves are no reliable [71].

Overall, the use of soil moisture sensors can make irrigation scheduling more accurate than weather-based model predictions [4]. This in turn improves environmental performance by decreasing the amount of nutrient leaching in runoff and to ground water, particularly is high soils with a high percolation rate [71, 73].

2.2.3 Irrigation Delivery

When estimating irrigation requirements and investigating water savings, it is important to understand the method by water is delivered to the soil. Looking at equation *E-21*, the irrigation efficiency can have a significant impact on the amount of water required for irrigation. Another significant factor is the uniformity of the delivery as this directly impacts turfgrass quality [4]. In turf irrigation there are three main techniques that can be considered: spray irrigation, subsurface drip irrigation and subirrigation.

2.2.3.1 Spray/Sprinkler Irrigation

The conventional technique for delivery of irrigation water to turfs remains sprinkler irrigation [4]. This is due primarily to its simplicity, reliability and comparative low capital costs. There are three main sprinkler irrigation techniques that are used:

- Irrigation through a portable sprinkler – This is an inexpensive option, but requires significant labour costs. It has also been noted that the sprinklers can be a target for theft [4].
- Quick coupling valves – This is in the intermediate range in terms of expense, but still requires some labour. Importantly irrigation using this technique is often inefficient [4].
- Automatic pop-up sprinklers – These require little labour, but can be quite expensive. Where designed correctly uniformity and efficiency can be quite high [4].

Irrigation using sprinklers has the benefit not only of being well established and understood, but also can easily be monitored visually, something that is missing from subsurface irrigation techniques [65]. The more expensive sprinklers are also more easily automated and a general rule of thumb for efficiency is that greater automation brings greater efficiency [4].

There are significant drawback from sprinkler irrigation however – the most significant being the uniformity of irrigation. In general the radial (or circular) precipitation from a sprinkler means that irrigation near the sprinkler head is generally more intensive than irrigation at a greater distance, simply due to the larger area the water must cover [4]. To improve uniformity considerable overlapping is generally required. The suggestion has been that using a triangular pattern gives a reasonable uniformity for greatest cost effectiveness [4]. The pressure applied will also influence uniformity with low pressures generally creating a donut pattern with more water delivery to the extremities than the centre and high pressures giving greater irrigation in the centre than the extremities [4]. Careful selection of pressure and pipework that can influence pressure is a must.

Another drawback is the influence of wind and evaporation [4]. High winds can significantly interfere with uniformity and also increase the rate of evaporation. Drop size is also an important characteristic. Small droplets lead to greater evaporative losses, but large droplets can be damaging to the turf and soil [8].

While sprinkler irrigation can still deliver the required volume of water for irrigation even if at low efficiency the way in which it is delivered can have unintended effects. Specifically, by applying water to the surface, the roots of turf tend to be smaller [45], particularly where irrigation is fairly regular [8]. This decreases the drought tolerance of the field as roots are unable to tap into deeper water reserves [45]. Reducing the frequency of surface irrigation is one way of reducing this effect and ensuring adequate rooting of turfgrasses [8].

Overwatering and runoff are also significant problems in sprinkler irrigation [65], particularly with high labour techniques [4]. Runoff is a particular concern to local councils during water restrictions as this is a visible sign of wastage to local residents and can generate increased complaints [65]. The reason for this can often be due to the rate of precipitation from the sprinkler (i.e. the rate at which water is applied). Where this exceeds the rate of percolation through the soil, runoff and ponding become more common. The selection of a sprinkler with a precipitation rate lower than the percolation rate should help reduce runoff and ponding [4].

Energy use also tends to be higher as extra pumps are required at many sites in order to regulate the pressure supplied [76]. This can be decreased somewhat though the use of variable speed pumps that can allow for the optimization of pressure requirements for irrigation on a regular basis [4].

2.2.3.2 Subsurface Drip Irrigation

Subsurface drip irrigation (SDI) applies water directly to the rootzone through the use of porous pipes or drip tapes with inbuilt emitters. The emitters are often designed for specific flow rates and developed in such a way as to ensure turbulence and minimise blocking [77]. Where the system has been well designed, the distribution uniformity of irrigation should be better than for spray irrigation [76, 78] and this is one of its most important benefits. It should be noted that the design of these systems is highly dependent on soil type and it permeability [79, 80]. While sand is well suited to SDI, clay requires a more dense system due to issues with distribution [80].

It is generally assumed that SDI is more water efficient and produces less runoff than spray irrigation, however there much scientific debate about this [81]. While the effect crop growth is generally undisputed (subsurface irrigation either reduces water requirements or significantly increase yields [76, 81]) the effect for turfgrass seems less pronounced [81]. While some studies specifically on subsurface turfgrass irrigation that have shown a decrease in water use (although this was not quantified) [65, 78], another more thorough study showed that the difference in irrigation application between SDI and sprinklers was negligible (465 mm for SDI versus 472 mm for sprinklers) [82].

Runoff and percolation issues have been shown to be reduced [65, 83] with one noting the number of complaints lodged for water-runoff at a university were zero, compared to six complaints for spray irrigation over a one year period [65]. Reduced runoff and percolation in turn improves the environmental performance of irrigation with less nutrients washing out after fertilizer application [78].

SDI also provides an opportunity to add nutrients directly to the rootzone. This has been found to increase efficiency of use, particularly for phosphates [81]. The lower leaching losses in turn contribute to improved environmental performance [83].

Other advantages of SDI include:

- Better weed management – by providing water only to the rootzone, germination of seeds cannot occur unless rainfall is significant [78, 81].
- Safer application of lower quality waters – in the case of irrigation with recycled water, lower qualities can be used due to the lack of contact between the water and users [5, 78]
- Decreased energy costs – this is due to the lower pressure requirements of SDI when compared to spray irrigation [78, 81]. These savings are more likely to be realised where pumping is provided onsite, such as for stored water or where the pressure from the potable water supply needs to be supplemented [65].
- Irrigation can occur at any time – this is important for fields under heavy use or in areas affected by winds [76, 81].
- Decreased maintenance – this is generally claimed as being due to the lower number of mechanical parts in the system and has been documented in some cases [65, 78]. The downside is that when maintenance does occur, it is more time consuming and expensive [81].

There are however disadvantages to the use of SDI, the most significant being emitter clogging. This can occur in a number of ways: (i) root intrusion, (ii) chemical precipitation and biofouling, (iii) soil clogging. Root intrusion has been documented in a range of studies [65, 81, 82, 84] and is the main cause for concern particularly for nutrient rich wastewater irrigation [85], however there are ways of avoiding it. Zoldoske found that irrigation systems that incorporated a herbicide into the plastic were highly resistant to root intrusion [65]. This technology is almost standard with the incorporation of Treflan into emitters becoming relatively common [86]. It is also possible to add a small amount of herbicide to the irrigation water to reduce root growth in the area of the emitter [76]. Another suggestion has been to use a high frequency of irrigation to produce a permanently saturated zone around the emitter to discourage root growth [76].

Table 2.17 Recommended water qualities for use in subsurface drip irrigation. Adapted from [5, 76, 87].

Parameter	Level of concern		
	Low	Moderate	High
pH	< 7.0	7 - 8	> 8.0
Bicarbonate (HCO_3, meq.L^{-1})	< 2	> 2	> 2
Iron (mg.L^{-1})	< 0.2	0.2 – 1.5	> 1.5
Manganese (mg.L^{-1})	< 0.1	0.1 – 1.5	> 1.5
Hydrogen Sulphide (mg.L^{-1})	< 0.2	0.2 – 2.0	> 2.0
Total Dissolved Solids (mg.L^{-1})	< 500	500 – 2000	> 2000
Suspended Solids (mg.L^{-1})	< 50	50 – 100	> 100
Phosphate (mg.L^{-1})	< 0.05	0.05 – 0.2	> 0.2

Chemical precipitation typically takes the form of iron, manganese or calcium salts [76]. Iron, manganese and phosphorus can also contribute to biofouling [5, 76]. Filtration of irrigation water should occur prior to use and will decrease this somewhat [76]. Chemical precipitation may still occur however and Table 2.17 contains the recommendations of Harris [76, 87] and the Australian Guidelines for Recycled Water [5] with regards to minimum water quality requirements for irrigation systems. These recommendations are also effective against some biological growth. Alternatively small concentrations (0.5 to 1 mg.L^{-1}) of a biocide such a chlorine may be able to reduce biofouling [87], though it should be ensured it is kept low due to its potential toxicity to turfgrasses [16].

Soil clogging is a particular concern during shut down of the irrigation system when a vacuum may form and potentially draw soil particles into the emitters [81]. This issue is best dealt with by utilizing best design principles and ensuring that air and vacuum release valve are appropriately placed in the system [76, 81].

Another significant limitation that is related to clogging issues is the ease with which the irrigation system can be monitored [65, 76, 78, 81]. While spray irrigation can be monitored visually for problems this is not the case for SDI. Instead secondary techniques including monitoring pressures and flows must be used [65, 81]. This can make it difficult to isolate a problem, and, as noted previously, where clogging occurs maintenance costs can be significant [81].

Salt accumulation is also cited as a point of concern in SDI systems, particularly where alternatively waters are used [79, 80, 84]. Where rainfall is insufficient to move salt from the rootzone growth may be impaired and SDI may not be suitable.

Another drawback is where a turf has overseeding requirements. For seed germination, water is generally required at the surface of the soil. While it is possible to design SDI systems is such a way [81] it is generally always supplemented by spray irrigation [76, 81]. This can be efficient during establishment of turfs, however if it is required annually for overseeding, SDI may not be suitable.

For more information of SDI, the Queensland Government Department of Primary Industries and Fisheries have a series of short reports about design and management of such systems [76, 77, 87-90].

2.2.3.3 Subirrigation

Subirrigation is the practice of artificially raising the water table to ensure water available to a turf, without exposing it to potential evaporation in the atmosphere. The water is stored below the root zone and is drawn up to the roots via capillary action [91]. Subirrigation systems essentially a large impervious lining (or pan) that is placed below the root zone and criss-crossed with perforated pipes that perform the job of water delivery and drainage [91]. This means that uniformity of irrigation is significantly higher than in sprinkler systems [1]. An overflow pipe ensures the artificial water table does not rise too far and waterlog the root zone.

At first glance the technique does not appear to be a water saving idea, however this is not the case [91]. Once the water reserve has been established, water use can be quite low. While the turf gets the water it needs, the capillary action limits the amount of water in the root zone and particularly at the surface reducing evaporative losses. This lack of water in the root zone also means that when rain falls there is less runoff and the rainfall can be utilized efficiently as the soil still has storage capacity [45]. Percolation losses are also reduced by the technique. Overall, water savings of 40-95% over sprinkler irrigation have been reported using subirrigation [1]. This is complemented by more extensive root growth that ultimately make a turf watered in this way more drought tolerant [45].

Due to its location below the root zone, subirrigation does not suffer from the root intrusion issues seen in SDI. Wilting of cool-season turfs commonly seen in spray irrigation, has not seen in subirrigated turfs [92].

Subirrigation can be performed in two ways, by maintaining a level water table or using a fluctuating water table. Krans showed a stable water table resulted in poorer yields when compared to both fluctuating water tables and sprinkler irrigation making this the more suitable technique [92].

The disadvantages of the technique are similar to those seen in SDI: capital investment is significant; maintenance, though less regular, can be costly when required; and monitoring can only be performed through secondary techniques [1]. The other significant disadvantage is the potential loss of pigmentation of the turf due to low dissolved oxygen content in the water [92]. While this was reported in older studies , it has not been in more recent ones [45], suggestion some of the problems with the technique have been overcome.

2.2.4 Storage Considerations

When considering using an alternative water source, it is important to consider how the water will be stored. Often water is available at a constant rate, such as in decentralized recycled water systems and sewer mining, or it is available when it is not needed. Under these conditions storage volumes will determine the reliability of the system. The material used to construct the storage will potentially impact the quality of the water. The three main water storage techniques used are water tanks, artificial ponds and lakes and aquifer recharge. Each of these is described below.

2.2.4.1 Tanks

Tanks are useful for storing water but typically are only economical on a small scale, due to the amount of metal or plastic that goes into the construction of the tanks. Cost estimates can be made using the equation (adapted from [93]):

$$C = 19.394V^{0.8473} \qquad E\text{-}22$$

Where V is the volume in litres and C is the cost in Australian dollars. While tanks in the kL range are affordable, ML sized tanks can become quite expensive.

The benefit of using tanks is that they are separated from the surrounding environment. This prevents evaporation of the stored water while also preventing the contamination from outside water. This is not to say that the water will not undergo some quality changes. Rain water tanks can be rich in microbes that, while it may at first seem a problem, appear to actually improve water quality [94]. On the other hand, the materials used to make the tank can corrode and leach into the stored water if it is too soft or the water is acidic [95]. Of particular concern are galvanised steel and copper components that can leach zinc and copper into the stored water [96, 97]. If the concentration of either of these species is too high it is particularly detrimental to the health of the turf [8]. Iron may also leach from steel based tanks, however at low levels of application iron has been found to be beneficial to turf in an irrigation water [9].

2.2.4.2 Artificial Ponds and Lakes

After a water has been treated, it should be of a suitable quality for storage in an artificial pond or lake. If the land is available this could be a less expensive option storage of large volumes of water. Another benefit of artificial lakes is the increased amenity and visual aspects of the storage. Storages designed to mimic natural conditions can lead to an increase to biodiversity in the area making the lake more pleasing to the general public, and potential create a useful open space for the local community. Increased biodiversity can also help reduce pests such as mosquitoes in the more stagnant water [98], particularly over the longer periods of water accumulation (typically winter). There is a potential negative from the increased biodiversity however in that contamination of the water from animal faeces becomes a potential water quality issue, both in terms of chemistry and biology. Artificial lakes are also more susceptible to environmental conditions in that evaporation will concentrate the water. This can possibly leads to cyanobacterial or algal blooms that will significantly impact the use of the water. Cyanobacteria will release toxins into the water preventing its use, while algae may release compounds such as surfactant that could influence the biology of soils that are irrigated using the water and ultimately impact on the nutrient uptake of the turf [16].

2.2.4.3 Aquifer Recharge

Aquifer recharge is another option for large volumes of water, where an aquifer is available. Storage in an aquifer helps to reduce the footprint of the storage making it more suitable where land area is an issue. It also means that environmental conditions will limit water losses with only exfiltration from the storage rather than evaporation an significant issue.

A secondary benefit comes from the long residence time and the loss of bacterial and viral contamination as a result. Studies of aquifer storage systems worldwide have shown highly efficient removal for *Campylobacter* (typical > 6 log reduction) and some removal efficiency for rotavirus and *Cryptosporidium* depending on residence time in the aquifer [99]. This is generally accompanied by changes in water chemistry, typically from leaching of geological materials [100]. This can result in a decrease in pH of the stored water [101]. The aquifer may also provide a small amount of nutrient reduction due to the presence of a subsurface microbial colony surrounding the injection site [100]. Organic compounds may also be transformed by similar processes. This will work best where the injection site is separate from the extraction site. The changes in water chemistry, particularly the loss of oxygen and increased mineral content, means that treatment may be required upon abstraction from the aquifer. This may simply be aeration [99] or other treatments common to groundwater. More information on groundwater treatment may be found in Section 3.6.3.

2.2.5 Turf and Soil Health

2.2.5.1 Introduction

Changing the source of n irrigation water can potentially have adverse impacts on the turf and soil quality. Negative impacts from toxicity, soil hydrophobicity and compaction are just some of the conditions that need to be avoided. The following is a general discussion of general water quality impacts.

2.2.5.2 Salinity

Salinity is probably the most pressing concern in the use of alternative water supplies. It can have severe negative impacts on both soil and turf quality. In general salinity refers to sodium ion content and to a lesser degree chloride ion content. However, it is often the ratio of sodium to other ions, particularly calcium and magnesium, that can determine its detrimental effects. This is due to the replacement of calcium and magnesium in soils with sodium where its concentration is high. This in general leads to structural changes in the soil, compaction and a loss in permeability for water making it harder to irrigate [102]. In extreme cases the loss in permeability can prevent oxygen transfer in the soil leading to the development of anaerobic zones and ultimately turf death. This is exacerbated on sportsgrounds where a high volume of traffic is common [16]. Saline toxicity comes in a number of forms and symptoms of saline stress will vary. Harvandi and Marcum have outlined the symptoms at various levels of stress [103]:

- Early stages: blue-green or light, bright green coloration coupled with irregular shoot growth
- Middle stages: blades increasingly wilted and darker green
- High salinity stress: burning of leaf tips, gradually extending down the length of the blade. Root zones are shallow and growth stunted.
- Extreme salinity stress: growth minimal, shoot density decreases, turf death.

Table 2.18 Maximum salinity tolerance for various turfgrass species. Adapted from [13]

Species	Salinity Tolerance
Distichlis spicata (seashore saltgrass)	35 dS.m^{-1}
Sporobolus virginicus (marine couch)	
Paspalum vaginatum (seashore paspalum)	25 dS.m^{-1}
Zoysia matrella (manilagrass)	
Zoysia pacifica (goudswaard)	
Puccinellia spp. (alkaligrass)	
Zoysia japonica (Japanese lawngrass)	14 dS.m^{-1}
Pennisetum clandestinum (kikuyugrass)	12 dS.m^{-1}
Agrostis stolonifera (creeping bentgrass)	10 dS.m^{-1}
Festuca arundinacea (tall fescue)	8 dS.m^{-1}
Buchloe dactyloides (buffalograss)	7 dS.m^{-1}
Lolium perenne (perennial ryegrass)	
Agropyron cristatum (crested wheatgrass)	
Festuca rubra (red fescue)	6 dS.m^{-1}
Bouteloua spp. (grama)	5 dS.m^{-1}
Bromus inermis	
Lolium multiflorum (Italian ryegrass)	
Poa pratensis (kentucky bluegrass)	4 dS.m^{-1}
Anoxopus spp. (carpetgrass)	3 dS.m^{-1}
Eremochloa ophiuroides (centipedegrass)	
Paspalum notatum (bahiagrass)	
Festuca brevipila (hard fescue)	
Festuca ovina (sheep fescue)	
Agrostis capillaris (colonial bentgrass)	2 dS.m^{-1}
Agrostis canina (velvet bentgrass)	
Agrostis gigantea (redtop bentgrass)	
Poa trivialis (rough bluegrass)	
Poa annua (annual bluegrass)	

To avoid these conditions a general recommendation has been made to keep irrigation water conductivity below 3000 μS.cm^{-1} as a minimum and preferably below 700 μS.cm^{-1} [102]. In general this type of salinity stress is considered more of an issue than sodium or chloride ion toxicity as turfgrasses are generally more tolerant of this [102] although it is highly species dependent. Table 2.18 provides a list of the salinity tolerances for a range of turf species. Soil type also plays a role however with clays at greater risk than sand. Highly saline waters are generally only recommended for irrigation of sandy soil for this reason [16]. The ANZ guidelines provide limits for couch grown on various soil types. It recommends conductivity values for irrigation water of 10800 μS.cm^{-1} on sand, 6100 μS.cm^{-1} on loam and 3600 μS.cm^{-1} on clay.

A more detailed way of determining the likelihood of salinity stress is to investigate the sodium adsorption ratio (SAR). The SAR is defined mathematically as [8]:

Table 2.19 Recommended SAR and conductivity values for the protection of soils. Adapted from [16].

	Degree of Problem		
	Negligible	Slight to Moderate	Severe
if SAR = 0 to 3 and EC	> 0.7	0.7 - 0.2	< 0.2
if SAR = 3 to 6 and EC	> 1.2	1.2 - 0.3	< 0.3
if SAR = 6 to 12 and EC	> 1.9	1.9 - 0.5	< 0.5
if SAR = 12 to 20 and EC	> 2.9	2.9 - 1.3	< 1.3
if SAR = 20 to 40 and EC	> 5.0	5.0 - 2.9	< 2.9

$$SAR = \frac{Na^{+}}{\sqrt{\frac{Ca^{2+} + Mg^{2+}}{2}}} \qquad \text{E-23}$$

where Na^{+}, Ca^{2+} and Mg^{2+} are the concentration in $meq.L^{-1}$. The SAR can be analysed with the electrical conductivity of the irrigation water according to Table 2.19 to determine likely effects. This should help maintain water permeability in the soil [16]. If the SAR is too high, it is possible to add lime to the soil or irrigation water to improve the water quality for irrigation. This is a common practice with recycled water in the United States.

As mentioned previously specific ion toxicity is likely to be an issue only in rare cases. While limits of 70 $mg.L^{-1}$ have been set to ensure no effects of sodium toxicity, no levels with severe effects have been recorded. It is also generally recommended that chloride be maintained below 70 $mg.L^{-1}$ or below 355 $mg.L^{-1}$ to avoid any serious effects of toxicity [16].

2.2.5.3 Boron

Boron is an essential trace nutrient for plantlife [8, 104], however high uptake of boron by plants can also lead to toxicity. Boron toxicity is considered a major issue in plants irrigated with a high boron water or grown on a high boron content soil. Boron toxicity typically stunts the growth of plants and can lead to spot formation of leaves that become necrotic. In turfgrasses boron will concentrate near the tips of blades and necrosis occurs here [104].

Boron can become an issue with some water sources, particularly seawater and recycled water. Desalination of seawater is typically performed by the reverse osmosis technique. While this is relatively efficient at removing most salts, it is less efficient for removing boron (about 30-40% is removed [105]). The result can be a relatively high boron content in the product water. Boron can also enter recycled water streams through boron-containing soaps and detergents, although the content is generally considered low [16].

Table 2.20 Relative boron tolerance of six turfgrass species. Adapted from [104]

Most Boron Tolerant	*Cynodon dactylon* (bermudagrass)
	Zoysia japonica (Japanese lawn grass)
	Poa pratensis (Kentucky bluegrass)
	Festuca arundinacea (Tall fescue)
	Lolium perenne (Perennial ryegrass)
Least Boron tolerant	*Agrostis stolonifera* (creeping bentgrass)

Compared to other plant species, turfgrasses are quite tolerant to boron levels [104]. Different turf species are also more tolerant than others. Table 2.20 gives the relative boron tolerances of six turfgrasses. While the Australian and New Zealand Guidelines for Marine and Fresh Water Quality state boron levels in irrigation water should be maintained below 0.5 $mg.L^{-1}$ [106], turfgrasses can tolerate concentrations up to 1 $mg.L^{-1}$ [16, 105]. Under high boron content in irrigation water it is generally recommended to remove the cuttings after mowing [16] as this is where boron is typically concentrated and will help to ensure no build up occurs. Also care should be taken if other plant species fall in the irrigation area or receive significant amounts of runoff. Soils may also retain boron from the irrigation water leading to later toxicity issues. While soils will adsorb boron to differing degrees evidence has suggested uptake is related more closely to the water content than soil content [107] and this should be considered the more important factor.

2.2.5.4 Metals

Metals in irrigation water can pose two significant threats: corrosion of irrigation equipment and toxicity to the turf. The first of these relates only to some species, with iron and manganese the two most important dissolved metals that can enhance biocorrosion [108-111] and other metals such as copper enhancing specific corrosion reactions. The studies performed during the development of the Australian and New Zealand Guidelines for Marine and Freshwater Quality standards however suggest that toxicity is the greater issue.

Table 2.21 shows the concentration limits recommended for irrigation waters by the Marine and Freshwater Quality Guidelines. They define two limits based around the length of expected use for the site. Where irrigation is anticipated for twenty years or less the short-term trigger value (STV) can be used, otherwise the long-term trigger value is more appropriate. The final column represents the contaminant loading limit or the maximum allowable concentration of a certain metal in the soil. After twenty years it is generally recommended that this concentration be analysed to ensure that the irrigation water is not adversely impacting the soil.

The effect of metals in irrigation waters can vary dramatically, and while many are necessary to plant growth, there is a very fine line between nutrition and toxicity. Some of the metals may interact. A good example is the effect of copper and zinc. Both of these metals act to prevent the uptake of iron so copper and zinc toxicity mimics iron deficiency. High concentrations of these two metals appear to be the most significant concerns in terms of alternate water sources [6]. Iron, on the other hand, is probably less of a concern as some studies have shown that low level iron applications using irrigation water is actually beneficial to turf growth [9].

Table 2.21 Recommended limits for metals concentrations in irrigation water. Long-term triggers apply to 20 years use, while short-term apply to 5 years use. Adapted from [106].

Element	Suggested Soil CCL (kg/ha)	Long-term Trigger (ppm)	Short Term Trigger (ppm)
Aluminium (Al)	-	5	20
Arsenic (As)	20	0.1	2
Beryllium (Be)	-	0.1	0.5
Boron (B)	-	0.5	*
Cadmium (Cd)	2	0.01	0.05
Chromium (Cr)	-	0.1	1
Cobalt (Co)	-	0.05	0.1
Copper (Cu)	140	0.2	5
Fluoride (F)	-	1	2
Iron (Fe)	-	0.2	10
Lead (Pb)	260	2	5
Lithium (Li)	-	2.5	2.5
Manganese (Mn)	-	0.2	10
Mercury (Hg)	2	0.002	0.002
Molybdenum (Mo)	-	0.01	0.05
Nickel (Ni)	85	0.2	2
Selenium (Se)	10	0.02	0.05
Uranium (U)	-	0.01	0.1
Vanadium (V)	-	0.1	0.5
Zinc (Zn)	300	2	5

Metal contents in alternative water sources are going to vary dramatically. In general, however understanding the catchment for the source will help in identifying what species may be an issue. In general industrial sources are a high risk both in terms of stormwater and recycled water. Stormwater catchments that include major roads such as freeways or large commercial/light industrial estates would also be potentially problematic. Rainwater or stormwater that is collected off metal roofs can also be an issue. While all these sources can be treated to reduce the concentration of metals, limiting catchments to residential sources with a small number of commercial sources will help to ensure the lowest possible metal loadings and therefore safest water for the turf.

2.2.5.5 Pesticides, Herbicides and Biocides

Pesticides and herbicides are obviously detrimental to turf growth even below parts per million concentrations. There are a large number of these compounds and they are not necessarily always present, but may come through in high concentration slugs. Testing in general is very expensive and regular testing to identify if any are present is not currently practical for large water projects let alone small decentralised systems. In general it is best to know the catchment. Agricultural sources of water could be a problem with pesticides as could some industrial sources. As with metals limiting the catchment area to residential sources is probably the best technique in avoiding potential problems with these compounds.

In general, biocides used in any alternative water scheme tend to be short-lived leaving little residual and rely on short residence times to ensure high quality water reaches the end use. The only biocide of concern is chlorine which can be added to recycled water at very high concentrations. Highly oxidising chlorine is toxic to plantlife and care should be taken to ensure the content in irrigation water is not too high. Scientific literature recommends aiming to keep residual chlorine below 1 $mg.L^{-1}$, although up to 5 $mg.L^{-1}$ will result in only moderate effects [16]. The addition of sodium metabisulfite to water can help remove chlorine, though at the expense of increasing salinity.

2.2.4.6 Carbonates

The bicarbonate and carbonate content of irrigation water is also critical in ensuring good quality soil and turf. High concentrations of carbonates in the presence of calcium will lead to precipitation and foliar deposits on the turf [5]. At very high concentrations these carbonates can also increase the soils pH leading to decreased soil permeability and bringing detrimental changes to microbial activity [16]. Literature recommendations suggest bicarbonate should be maintained below 90 $mg.L^{-1}$ and definitely not above 500 $mg.L^{-1}$ [16].

2.2.4.7 Phosphates and Nitrogen

Phosphates and nitrogen source are vital to the growth turf. Introduction of these important fertilizers to the grass as part of the irrigation water will ensure a constant, low level application that is believed to be beneficial [16]. Total nitrogen in particular is usefully applied in small doses over a long time period as this appears to improve the health and colour of the turf [112]. The requirements do vary between species as shown in Table 2.22.

The benefits of high nutrient content irrigation waters also apply to biological growth in storage ponds and pipework, however. This could ultimately lead to biofouling of irrigation pipework and the failure of the system. Excess nitrogen can also be detrimental to the turf and actually result in the stunting of growth. The Marine and Fresh Water Quality Guidelines suggest maintaining phosphorus levels below 0.05 $mg.L^{-1}$ and nitrogen below 5 $mg.L^{-1}$ for long term use (i.e. greater than 20 years of application) [106]. Short term use will be heavily site specific, but concentrations of up to 125 $mg.L^{-1}$ for nitrogen and 12 $mg.L^{-1}$ for phosphorus may be achievable. The Australian recycled water guidelines are slightly relaxed and suggest that no effects of nitrogen can be seen at irrigation water concentrations below 30 $mg.L^{-1}$ [5]. In terms of phosphorus they also suggest maintaining contents below 0.05 $mg.L^{-1}$ or monitoring of the system after 40 years at concentration around 0.2 $mg.L^{-1}$. Higher concentration may be possible but would require more regular monitoring of the irrigation system to ensure no blockage has occurred.

Table 2.22 Nitrogen requirements for different turfgrass species. The requirements are given in grams per square metre per growing month. The data was adapted from [9].

Species	Common Name	N requirements ($g.m^{-2}.month^{-1}$)
Agrostis canina	Velvet bentgrass	2.4 - 4.9
Agrostis capillaris	Colonial bentgrass	2.4 - 4.9
Anoxopus	Carpetgrass	1.0 - 2.0
Buchloe dactyloides	Buffalograss	0.5 - 2.0
Cynadon dactylon	Bermudagrass, couch	3.9 - 8.8
Eremochloa ophiuroides	Centipedegrass	0.5 - 1.5
Festuca Arundinacea	Tall fescue	2.0 - 4.9
Festuca Rubra	Red fescue	1.0 2.4
Lolium multiflorum	Italian ryegrass	2.0 - 4.9
Lolium perenne	Perennial ryegrass	2.0 - 4.9
Paspalum Notatum	Bahiagrass	0.5 - 2.0
Poa annua	Annual bluegrass	2.4 - 4.9
Poa pratensis	Kentucky bluegrass	2.0 - 3.4
Poa trivialis	Rough bluegrass	2.4 - 4.9
Stenotaphrum secundatum	St Augustinegrass	2.4 - 4.9
Zoysia	Japanese lawngrass	2.4 - 4.9

2.2.5.8 Oil and Grease

Some water sources will contain oil and grease compounds that if left untreated are detrimental to irrigation. Oil and grease compounds are a range of chemicals that are soluble in non-polar (or organic) solvents. When applied to a soil rarely they are degraded by microbial communities in the soil [113]. However, when applied regularly as part of irrigation water a build-up of compounds will occur [113]. The hydrophobic nature of the chemicals increases the soil’s water repellence and ultimately reduces the effectiveness of irrigation [113]. They may also introduce water poor sections to the soil as the oils cannot be flushed out by rainfall or irrigation [113].

2.2.6 Human Health

2.2.6.1 Introduction

One of the primary concerns expressed about the use of non-potable water is the potential effect on human health. This comes from the perceived health risks associated with different types of non-potable water, particularly pathogens and endocrine disruptors in recycled water. The following is a discussion of the actual health risks associated with non-potable water use for irrigation purposes and ways to reduce these risks. There are generally two main categories of health risks: chemical of concern and pathogens. Though both are considered in the following discussion, pathogens ultimately represent the greatest risk. This risk is essentially eliminated where the Australian and Victorian guidelines are followed in the establishment and the operation of a project.

2.2.6.2 Chemicals of Concern

Chemicals of concern refers to trace elements present in recycled water either from industrial waste products or from health related excretions. Other chemicals may also enter storm and rainwater after settling on the ground or rooftops and being collected by the rainfall.

Recycled Water

There are a number of classes of compounds in the chemicals of concern category, including mutagens and carcinogens. However the two groups generally discussed in recycled water are endocrine disrupting compounds (EDCs), compounds that have an effect on the hormonal balance of an organism, and pharmaceutically active compounds (PhACs), compounds derived from pharmaceuticals that take part in the body chemistry of an organism. One of the main problems with chemicals of concern is the large number of potentially harmful compounds or compounds that are currently unknown that may have an impact.

It is generally accepted that wastewater treatment processes remove amounts of these compounds [114]. Research in Australian recycled water plants has suggested that undetectable amounts in water after tertiary treatment are further reduced by microfiltration and reverse osmosis (dual membrane filtration) processes [115]. This is evidenced by detectable quantities in the RO brine. The trace level of most compounds of concern in recycled water in general suggests there is little risk to their presence in non-potable applications [116]. The unknown nature of the compounds do, however, raise some cause for concern [117] although this is a point of contention.

Stormwater and Rainwater

Stormwater and rainwater have the potential to collect chemicals from the catchment that may have accumulated on surfaces or result from the degradation of surfaces. In the past recommendations have been made not to collect the "first flush" of rainwater or stormwater because it was believed to be the most contaminated. Recent research however suggests this is not the case [118] and the Australian guidelines do not recommend this to try to control chemical contamination [6].

In rainwater use water quality would generally be high, but can be reduced by the presence of certain characteristics of a roof. The Australian guidelines for stormwater use strongly recommend using rainwater, or roof water, only where the following are not present [6]:

- Copper or zinc roofing materials
- Public access (with the exception of maintenance access)
- Vehicular access
- Structures above a roof that may rust or corrode or provide a resting place for birds
- Discharge, overflow or bleed-off/blow-down pipes from roof mounted appliances such as air-conditioning units, hot water services and solar heaters
- A flue from a slow combustion heater that does not meet the relevant Australian standard.
- A chimney or flue from any other process
- Exposure to chemical sprays from within the building (for example spray paint)
- Significant atmospheric deposition of pollutants (for example, from neighbouring industrial facilities)

Other issues may include lead and bitumen based materials, asbestos or preservative treated wood. While a project need not be precluded where any of these are present, treatment may be required to prevent human and environmental contamination, although the Australian guidelines feel the risk is suitably low that the exposure controls required to manage biological risks would be sufficient to protect against chemical risks [6].

Stormwater quality is also highly dependent on what may be in the catchment area. Where a catchment is primarily residential and commercial the risk is considered to be low and effectively controlled by the actions taken to manage biological risks [6]. However some issues that must be considered are outlined below:

- Industrial facilities – can generate high levels of metal and hydrocarbons
- Major roads, i.e. tollroads and freeways – can generate high levels of metals and hydrocarbons
- Agricultural land – can generate high levels of pathogen and nutrient runoff
- Catchments with a high quantity of metal roofs – can generate high metal loadings
- Streambank erosion and construction activity – can generate high levels of suspended solids and turbidity.

In each of the above cases an in-depth study must be undertaken of the catchment and considered in some detail. Extra treatment of the water may be required. Users should refer to the Australian guidelines in such situations.

General

For all chemicals of concern to have an effect, large quantities have to be consumed on a regular basis [114]. This would require someone to ingest copious amounts of water over a long time period. In public space and sportsground irrigation such a situation is not likely to occur. The main concerns would be with accidental consumption and cross connection with potable water systems. These issues are discussed in Section 2.2.6.4.

2.2.6.3 Pathogens

Pathogens are biological agents that cause illness in their host. Table 2.23 lists the more common examples of pathogens present in alternative water source. These fall largely into four classes: bacteria, viruses, protozoa and helminths [119]. In raw sewage these tend to be enteric pathogens (meaning they are common in the intestines of humans and therefore in human sewage), however recycled water and other water sources may also contain opportunistic pathogens (meaning they take advantage of favourable breeding conditions and can be found in almost any location where conditions are right). In general, although enteric pathogens are threats to human health, their nature means that their source is well-known and they can be easier to control. Opportunistic pathogens on the other hand can enter a system after disinfection techniques, via soil or air, and present a greater, unknown threat.

Table 2.23. Common pathogenic species in alternate water sources.

Pathogen Type	Species
Bacteria	*Legionella* spp. *Klebsiella* spp. *Salmonella* *Campylobacter* Pathogenic *Escherichia coli* *Shigella* spp. *Yersinia* spp. *Vibrio chloerae* Atypical *Mycobacteria* *Staphylococcus aureus* *Pseudomonas aeruginosa*
Viruses	Enterovirus Adenovirus Rotavirus Norovirus Hepatitis A Calicivirus Astrovirus Coronavirus
Protozoa	*Cryptosporidium* *Giardia* *Naegleria fowleri* *Entamoeba histolytica*
Helminths	*Taenia* (tapeworm) *Taenia saginata* (beef measles) *Ascaris* (round worm) *Trichuris* (whipworm)

To determine pathogen concentrations and effects, indicator organisms and reference pathogens are used respectively. Comparison of indicator organisms and reference pathogens before and after treatment serves to act as a guide to reduction effectiveness (most commonly defined as a log reduction that is to say how many orders of magnitude the concentration has decreased) across the entire class. Reference pathogens on the other hand have been established by the Australian Guidelines for Water Recycling [5] to assess the consequences of exposure and assist in determining the appropriate level of reduction required by the treatment process.

The four classes of pathogens and their indicator and reference organisms are discussed below:

Bacteria

Bacteria are the most common pathogens. They are unicellular organisms that can breed independently of a host. Bacteria typically have multiple host types, meaning they are not exclusive to humans and can be spread through other animals. Typically quite large populations are required for infection to occur. They are largely enteric and their populations can be reduced effectively using disinfection as part of a wastewater treatment program. They can never be fully eliminated however, and in storm and recycled water systems some biocide (typically in the form of chlorine) must be used to ensure the population does not re-establish [114]. Some opportunistic pathogens are also a concern, particular those picked up in dust and dirt. There are growing concerns about *Legionella* becoming a greater threat in water storage facilities as dust becomes more common in the dry, warm conditions around Melbourne.

Table 2.23 shows the typical log reductions in pathogenic species from various treatments. From this it can be seen that bacterial removal is effective with membrane filtration, reverse osmosis and biocidal techniques such as chlorination, ozonation and UV disinfection. These will focus on enteric bacteria reduction and will most likely be in place at the treatment plant providing the recycled water. However, as previously noted, bacteria do not need a host to multiply and opportunistic bacteria may enter the water through other sources. This means that some onsite precautions may be required to ensure regrowth does not occur. For details on this please see Section 2.2.6.5.

The presence of bacteria in water is typically measured using faecal coliform counts or *E. coli*. The reduction of these common enteric bacteria is believed to be an effective measure of the reduction of bacteria in general. The reference pathogen for bacteria, according to the Australian Guidelines is *Campylobacter* [5]. This is due to its being the most common cause of bacterial gastroenteritis in Australia.

Table 2.23 Indicative log reductions for various treatment processes. Adapted from [5]

Treatment	Indicative log reductions						
	E. coli	**Bacterial pathogens**	**Viruses**	***Giardia***	***Cryptosporidium***	***Clostridium perfringens***	**Helminths**
Primary Treatment	0 – 0.5	0 – 0.5	0 – 0.1	0.5 – 1.0	0 – 0.5	0 – 0.5	0 – 2.0
Secondary Treatment	1.0 - 3.0	1.0 – 3.0	0.5 – 2.0	0.5 – 1.5	0.5 – 1.0	0.5 – 1.0	0 – 2.0
Dual media filtration (w/ coagulation)	0 – 1.0	0 – 1.0	0.5 – 3.0	1.0 – 3.0	1.5 – 2.5	0 – 1.0	2.0 – 3.0
Membrane filtration	3.5 - >6.0	3.5 - >6.0	2.5 - > 6.0	> 6.0	> 6.0	> 6.0	> 6.0
Reverse Osmosis	> 6.0	> 6.0	> 6.0	> 6.0	> 6.0	> 6.0	> 6.0
Lagoon Storage	1.0 – 5.0	1.0 – 5.0	1.0 – 4.0	3.0 – 4.0	1.0 – 3.5	-	1.5 - > 3.0
Chlorination	2.0 – 6.0	2.0 – 6.0	1.0 – 3.0	0.5 – 1.5	0 – 0.5	1.0 – 2.0	0 – 1.0
Ozonation	2.0 – 6.0	2. 0 – 6.0	3.0 – 6.0	-	-	0 – 0.5	-
UV Irradiation	2.0 – > 4.0	2.0 - > 4.0	>1.0 adenovirus, > 3.0 enterovirus, Hepatitis A	> 3.0	> 3.0	-	-
Wetlands (surface flow)	1.5 – 2.5	1.0	-	0.5 – 1.5	0.5 – 1.0	1.5	0 – 2.0
Wetlands (subsurface flow)	0.5 – 3.0	1.0 – 3.0	-	1.5 – 2.0	0.5 – 1.0	1.0 – 3.0	-

Viruses

Viruses are the smallest pathogens. They are highly contagious, only requiring a small number to cause infection (10 viral particles are often enough [114]). They have a narrow host range, meaning viruses commonly found in birds will not easily jump to humans. They are also unable to replicate outside the host. This means that disinfection processes can reduce a virus to levels below that required for an infectious dose and that the population should not re-establish. Consequently, where an effective disinfection programme is in place at the water source, viruses should not pose a significant risk. This view is supported by the World Health Organisation's assessment of pathogen risks in recycled water [119]. Having said this, the more significant health effects from viral infection and lower infectious doses leads to greater log reduction requirements by the Australian guidelines [5]. This in general means that viral risks dictate the treatment and disinfection required in recycled water.

Virus removal can be effective with options such a dual media filtration, reverse osmosis and ozonation (Table 2.24). As was noted previously, as long as the tolerable risk is achieved at the water source, no significant risk will exist at the end use because viruses need a host to replicate.

While detecting the presence of specific viruses is possible, it is expensive. The more common approach is to use faecal coliforms as an indicator of when viruses might be present and take corrective action accordingly. This is because the test for faecal coliforms is easier, cheaper and more reliable than virus analysis. The reference pathogens as outlined by the Australian guidelines are rotavirus and adenovirus [5].

Protozoa

Biologically, protozoa are unicellular organisms, distinguished by the presence of a nucleus and outer membrane. More importantly they can exist outside a host as dormant cysts or oocysts that will activate in the host under the right conditions. The main host is man, although some other animals may affected. Common species are *Giardia lamblia* and *Cryptosporidium parvum* [114]. They are highly infectious requiring as few as 10 (oo)cysts for infection to occur. In terms of their inactivation however, they are the least understood of the pathogens.

Due to their large size, filtration techniques are often best for reducing protozoa levels as indicated by Table 2.24. UV irradiation has also been found effective in inactivating (oo)cysts and is currently used for this purpose by Melbourne Water at Western Treatment Plant. Chemical disinfection (chlorination and potentially ozonation) on the other hand appear to be less effective than with other pathogens. As with other pathogens the focus of removal is on the water source.

In the past faecal coliform counts were used to determine the efficacy of removal of (oo)cysts, however research has shown that there is little correlation between coliform kills and (oo)cysts kills [120]. Cyst counts are now more commonly performed, but recent investigations have suggested that this may not be a reliable indicator as between 75 and 97% of cysts after treatment are incapable of activating [121, 122]. Consequently, (oo)cyst counting will lead to a high number of false positives. However, the large rate of (oo)cyst deaths in treatment plants means that protozoa are not consider a significant threat in recycled water [121].

As noted above (oo)cyst counts of *Giardia* and *Cryptosporidium* are typically used as an indicator for protozoa. By the Australian guidelines the reference pathogen is the more difficult to remove *Cryptosporidium parvum* [5].

<u>Helminths</u>

Helminths are parasites such as hook worm, round worm and whip worm that reside in the stomach and intestines of a host. They generally have complex life cycles, requiring intermediate hosts to activate. The three previously mentioned are of greatest concern as they have no intermediate host [114]. They are classified as the greatest risk in using recycled water by the World Health Organisation [119] although their occurrence and removal through filtration and detention systems (see Table 2.24) limits their impact in Australian alternative water sources.

Helminths are rarely tested on a regular basis in Australian recycled waters, typically being removed by filtration or pond detention. In Victoria checks are generally performed to ensure that the treatment techniques effectively remove helminths on start up. They should not pose a significant threat in irrigation, however they are of concern in agricultural use. Open spaces that may be used or occupied by farm animals are of particular concern and greater care should be used when assessing these sites for recycled water use. In terms of reference pathogen, the Australian guidelines state that *Cryptosporidium parvum* is an adequate measure for helminths as well as protozoa [5].

<u>State and National Guidelines</u>

The Australian guidelines [5-7] focus primarily on the health effects of alternative water use and any consideration of this issue should be focused around the most current version of these. The guidelines ask for each user to perform a quantitative risk assessment aimed at producing "fit for purpose" water. This targets a reduced potential for pathogenic infection below a tolerable risk threshold (in this case 10^{-6} Disability Adjusted Life Years). Overall, the guidelines are designed to allow for greater flexibility in water treatment and use options. The various guidelines have set specific log reduction targets for municipal irrigation as shown in Table 2.25. Although there is still some potential for variation this is a good target range. In order to achieve the required log reduction there are two paths, the first is treatment with the log reductions shown in Table 2.24. The second is in exposure reduction controls. These are listed in Table 2.26. It is important for public space and sportsground professionals to understand these requirements as they are often used to achieve the desired health effects and shift the responsibility from water providers to water users. Those responsible for irrigation must ensure that any criteria outlined as part of the provision of recycled water are followed appropriately.

Table 2.25 Log reduction requirements for alternative waters to be used for municipal irrigation. Adapted from [5, 6]

Water Source	Activity	Log reductions			
		Cryptosporidium	Rotavirus	Campylobacter	Nominal Minimum
Black Water	Municipal irrigation	3.7	5.2	4.0	5.3
	Municipal irrigation + Dual reticulation	5.0	6.4	5.1	6.5
Storm Water	Municipal Irrigation	2.2	2.4	2.0	2.5
Rain Water	Municipal Irrigation	-	-	-1.1	No treatment required

Table 2.26 Log reduction equivalents from on-site controls. Adapted from [5]

Control Measure	Reduction in exposure to pathogens
Withholding period (1-4 hours)	1 log
Spray drift control (microsprinklers, anemometer systems, inward throwing sprinklers)	1 log
Subsurface irrigation	5-6 logs
No public access during irrigation	2 logs
Buffer zones (25-30 m)	1 log

As an example of the implemention of these guidelines, consider a public open space to be irrigated with recycled water. A the bacterial, viral, protozoan (B,V,P) log reductions of 3.7, 5.2, 4.0 are required. Using secondary treatment coupled with chlorination the log reduction achieved is 6, 3, 1. A further log reduction of three is therefore required at the site of irrigation to ensure public safety. This can be achieved by ensuring no public access during irrigation (log reduction of 2) and one of the following:

- Withholding period, preventing public access for four hours after irrigation (log reduction of 1)
- A 25 to 30m buffer zone (people prevented from entering) around the irrigated area (log reduction of 1)
- Control of spray drift by using inward throwing sprinklers (log reduction of 1)

Water treatment to a higher quality (for example that uses secondary treatment followed by membrane filtration and reverse osmosis giving a B,V,P log reduction of >6, >6, >6) may not require exposure reduction controls, while other water treated to a lesser degree may need significantly more. Each recycled water project will be different and must be assessed on an individual basis.

2.2.6.4 Cross Connection and Accidental Ingestion

Cross connection and accidental ingestion represent one of the most significant health risks in non-potable water uses. Though ingestion is the primary method for infection by enteric pathogens, the risk of infection is generally low. The continuous ingestion of non-potable water will significantly increase the risk however. There have been a number of well-publicised cross connection issues recently. What is important to note about them is that they are generally the result of human error and require strict management controls to be prevented.

Where a high quality of water is used very large volumes would be required for any effects to be seen [114]. Lower quality water may present a risk where biological control have not been put in place. People's perceptions of the water may not reflect this however. In most cross connection cases people report (generally retrospectively) gastrointestinal illnesses. Though these claims may be justified, there is also a degree of paranoia that results from the discovery that the water they have been drinking was not what the drinker believed it to be and there is no way of confirming this retrospectively. Consequently it is important to manage the risk of cross connection and accidental ingestion on site effectively.

Ensuring a non-potable water system is free from cross connections can be performed using a two-pronged approach: differentiation of the non-potable water system and the potable water; and system tests to ensure the water is what it is. It is also worth mentioning that there is a certification course for plumbers with regards to recycled water run by the local water provider. The Plumbing Industry Commission in Victoria also has guides to recycled water plumbing.

The most well known aspect of recycled water pipelines is the need for a colour differentiation from potable. The purple pipelines are standard throughout the world and a legal requirement in Australia [123]. Furthermore the marking of the recycled water pipelines and taps (with removable handles) as non-potable water is a legal requirement and can prevent accidental ingestion.

Some parts of the United States require that recycled water pipelines running in parallel to potable water lines be offset diagonally (ie both vertically and horizontally). This is believed to reduce the risk of accidental cross connection. In Victoria the only legal requirement is a separation of recycled water pipelines from potable of 100 mm above ground and 300 mm below [123]. Also there is a requirement that connections to recycled water taps and meters have different sized threads in order to minimise the possibility of cross connection. Another option that has been suggested is the use of pipes of different sizes. Where the potable water system is not used for fire protection and can be made smaller, this has the added benefit of ensuring water quality is maintained. In general the long residence times of potable water in large pipelines reduces the water quality. Reducing pipe size decreases the residence time and provide better quality water.

Testing of recycled water systems can be typically performed in two ways. The first is a standard in most residential reuse schemes in the US and involves the depressurizing of the recycled water system once a year. A similar system can be used in an industrial application where the recycled water system can be depressurized during major plant shutdowns allowing for a thorough check of the system.

The alternative is more extreme but is under consideration in Cary, USA after their recent cross connection problems. After a new property is connected to the recycled water system Cary officials will now test water directly from the tap of key properties. The main differentiating parameter in recycled water will vary with treatment conditions, however conductivity and chlorine residual are two key factors that generally vary. A similar simplified system may be achieved using conductivity or chlorine residual in industrial situations, with check being performed after major plumbing operations or plumbing where potable water systems were affected.

2.2.6.5 General Controls – Disinfection

The general control to protect human health in alternative water uses are guidelines outlining allowable uses based on the assessment of pathogenic health risks and barriers between existing pathogens and people. These barriers will take the form of treatments and exposure reduction controls as outlined previously. One of the more common controls used across all water types is disinfection. It is important to remember that the disinfection occurring at the treatment stage significantly reduce the presence of pathogen, but not completely eliminate them. Also, bacteria are able to regrow without a host and, as such, can increase in population where the water has a large residence time, i.e. is left standing for a long period of time. In the case of recycled water, water providers typically dose the water with large amounts of chlorine to both reduce pathogen populations and to maintain some residual amount to prevent regrowth. However this is depleted over time. As a general guide recycle water should still be suitable for use where a residual greater than 0.3 $mg.L^{-1}$ is maintained. Other water sources should be used as soon as treatment has occurred [124]. If this is not possible a biocide program may be required by the user. Though this is unlikely to be the case it is discussed briefly here.

In order for biocidal control to be effective, the dosage should be scientifically selected. A successful program will [125]:

- Know the target organisms

- Select the right biocide and its concentration
- Perform a scientific determination of the dosing frequency
- Monitor the control program
- Monitor attachment of micro-organisms to surfaces

In general oxidising agents are the most effective biocides as they act indiscriminately and organisms cannot build up a resistance to them [125]. They do, however, suffer from significant interferences reacting with many oxidisable substances such as organics. The main oxidising agents that would be considered in an irrigation project are:

- Chlorine. In swimming pools and water treatment this is typically added as sodium hypochlorite. The issue of salinity however may make the more expensive calcium hypochlorite a more appropriate choice. This disinfection is highly non-selective and suffers major interferences from ammonia and other nitrogen compounds that are beneficial to turf irrigation as nutrient sources. Its residual is easy to measure, but disappears quickly encouraging regrowth [125]. Importantly chlorine is toxic to turf species and any residual must be maintained below 5 $mg.L^{-1}$ and preferably below 1 $mg.L^{-1}$ [16]. This means low level of continuous dosage are more appropriate than shock dosing when regrowth becomes an issue.
- Chloramination. Chloramines, formed through the reaction of chlorine with ammonia, are becoming more popular primarily due to their high selectivity when compared to chlorine. This means they are less corrosive to the environment in which they are used and have a longer lasting residual. However, as chloramines is less oxidising than chlorine it is slightly less effective and bacteria have been seen to develop a resistance [126].
- Ozone. The decomposition intermediates of ozone are particularly effective as a biocide. Unfortunately, ozone is not stable in water and will not maintain a residual to prevent regrowth. It also breaks down organics to short chained, oxygen-rich species that promote bacterial growth [125].
- UV irradiation. This is most effective at a wavelength of 253.7 nm [125]. It lacks residual limiting it to point of use disinfection. An important limiting factor is turbidity. Turbidity above 1.5 NTU seriously reduces the effectiveness of disinfection. Some storm events can result in very high turbidity levels and pretreatment to remove solids may be required in some systems.
- Hydrogen Peroxide. While not effective on its own, it can be used in conjunction with UV irradiation to generate highly oxidising species that are both bacteriacidal and sporicidal [125].

Oxidising agents, though effective may also be problematic in their potential threat to steel, wood [124] and turf species [16]. Large dosages should be avoided and continuous, low levels applied instead. While other biocides are available they are probably not applicable to irrigation due to their cost.

2.2.6.6 Employee Health Protection

There are a number of important steps that can be taken to ensure employee health and safety when using non-potable water. It should be remembered that the water quality from any other than a potable supply should be considered non-potable. Australian guidelines for using recycled water, including stormwater, give treatments and control that make a water fit for purpose only and not necessarily for drinking. The steps you would take to protect employees may vary depending on the different water qualities, sources and their use and are generally outlined in the Victorian and Australian guidelines [5-7, 123] (please refer to these documents for the most up to date protocols). These protocols should be communicated as part of an induction for all people (direct employees and contractors) that are on site during irrigation or in direct contact with the water used for irrigation.

- Employee and contractors should understand what uses of the water are acceptable and what are not. They should also be aware of any controls required for irrigation using the water.
- Food, drink and cigarettes should not be consumed where non-potable waters are used.
- After using recycled water employees should wash their hands immediately
- All wounds should be covered with a waterproof dressing when working with non-potable water.
- Any skin rashes of illnesses should be reported to a supervisor who will in turn report to an OH&S specialist for investigation of the incident.
- Workers with dermatitis, chronic illnesses or weakened immune systems (either due to illness or medication) should be assessed by a medical professional before using or working in the vicinity of recycled water.
- Where raw sewage or Class D recycled water is used on site (i.e. where treatment is provided onsite) immunization may need to be considered against particularly harmful viruses such as hepatitis. This applies to worker who will be in contact with the water or around the treatment plant.
- Where stormwater is used hepatitis A immunization is generally recommended.
- All non-potable water taps should be labelled as being such, and should have the tap itself removed when not in use. There should be signs prominently displayed around the site indicating that non-potable water is used onsite.
- All employees should be made aware of procedures or problems related to the use of non-potable water. There should also be encouragement to report incidents.

2.2.6.7 Animal and Livestock Health

This report has not been prepared to consider agricultural sites. There is always the issue of domestic animals being present from organised groups such as obedience and agility training as well as casual users of sports fields and open spaces. Some turfed spaces are also occasionally used for fairs, circuses and agricultural shows. Consequently the potential effects to animals should be briefly considered.

There are a number of animal-based pathogens that may be present in a number of water sources particularly recycled water and stormwater. These are unlikely to be present in quantities similar to human-specific pathogens, but there are some pathogens that are also of concern to other animals, for example *Giardia lamblia* is also capable of infecting domestic cats and dogs [127]. While the Australian guidelines in general don’t consider animals, the risk assessment they propose has the ability to be expanded if a dose-response value for the infection of the animal can be determined. It may be appropriate to consider the health implications to animals, where these commonly use a site, using the Australian guidelines as a template.

Of all the animals to consider the most important are pigs. The main risk is the helminth *Taenia solium*, or pig measles. This tape worm uses pigs as an intermediate host. If an infected pig is consumed by humans a particularly severe infection results that can lead to serious neurological effects. As a consequence of this federal government regulations forbids the use of recycled water where it may contact pigs or pig fodder [5].

2.2.7 Perceptions

2.2.7.1 Public Perception

When considering non-potable water for irrigation it is important to understand how users will react. In a lot of cases the reaction will be negative. There is much discussion in the media about the significant energy requirements of desalination. There is also considerable discussion in the literature and media about the "yuck" factor associated with most non-potable waters, while for rain and storm water this is not as severe. While rain and stormwater are not immune to this effect, the strongest reaction is typically reserved for recycled water. It is considered a psychological aversion that arises from the belief that after contact with sewage the recycled water is tainted or contaminated. Similar psychological aversion can occur for stormwater which must have had contact with dirty and contaminated roads, footpaths and carparks not to mention industrial sites and hospitals. A study into the psychological effects of drinking different type of non-potable water and from eating foods grown with the same waters showed 20% of respondents suffered a feeling of disgust despite the fact that the sample was actually potable water [128]. Psychological effects will not be easy to overcome.

Investigations into public acceptance typically look at domestic uses and focus on potentially adding a traditionally non-potable water to a drinking supply. These have highlighted some important trends:

- Public acceptance is strongly tied to the intimacy of use [128]. That is to say the closer the water comes to a person, the more likely they will be opposed to it. Irrigation water has a fairly low intimacy of use and will suffer from less opposition than drinking or dual piping around the home.
- Public acceptance will decrease when a use is salient [129]. This is the equivalent of the NIMBY (not in my backyard) effect. While people may be in favour of using non-potable water for irrigation in principle, when told it will be happening at their local park or sports field opposition will increase.
- Public acceptance of recycled water is directly related to trust [130]. This is probably the most important aspect of recycled water use. The public will be more accepting of recycled water where they feel the proponents (the government, water authorities or company producing the water and the end user) can be trusted. This will also mean that the process by which a project advances should be open and transparent so people can understand how the decision process occurred.
- Public acceptance is related to knowledge [131]. This is an obvious relationship and may be addressed through community education and outreach. However, the success of these programs in overcoming the "yuck" factor may be limited, as this feeling is psychological in nature and cannot be considered the result of a "rational" decision. The Australian Guidelines for Recycled Water contains a chapter devoted to the development of community outreach and education programs [5].

As stated earlier public acceptance of water uses tend to focus on domestic applications such as drinking or washing. Irrigation of public spaces, golf courses and sports fields are typically considered to be generally acceptable to the public. This is reflected in studies that suggest for recycle water that acceptability lies in the range of 82 to 97% [129, 132]. There are different degrees of acceptability however. The terminology used in the studies above often accounts the variability in results. High acceptability is seen for golf courses and parks [132], while this decreases when described as schoolyards and playing fields [129]. This could be related to perceived exposure and the protection of family from exposure from perceived threats.

There will also be variation with different water sources. Dolnicar and Schafer [133] have investigated the acceptability of using recycled water versus desalination seawater for a number of applications. For municipal irrigation purposes it was shown that acceptability was 10-11% higher for recycled water (82-83%) over desalinated seawater (71-72%). This was largely associated with the energy requirement and environmental impacts of desalination when compared to producing recycled water. In general recycled water was deemed more appropriate for almost all external uses that did not involve direct contact.

Other comparative studies, looking at recycled water, grey water and storm water, have focused on the intimate use of drinking water and therefore may not be valid for evaluating irrigation acceptability. However, environmental concerns do not vary significantly between these water sources and psychological effects are likely to rule. The trends therefore may be considered valid. One of the more extensive studies was performed by the CSIRO and looked at perceived health risks and feelings of disgust associated with stormwater, grey water and recycled water [128]. In terms of drinking, the perceived risks were seen in the order from best to worst stormwater (~58% perceived health effects), grey water (67%) and recycled water (79%). Feeling of disgust followed a similar trends with 5% disgusted by stormwater, 10% for grey water and 22% disgusted by drinking recycled (sewage) water.

Though there are no clear studies into acceptability of different alternative water sources for irrigation, an order from most acceptable to least, may be derived from the above studies: stormwater as most acceptable followed by grey water, recycled water, and finally desalinated seawater as the least acceptable.

2.2.7.2 Employee Perception

Maintaining a positive image to the use of non-potable water onsite is also a very important issue. Negative images or publicity can halt a project in a similar way to community objections. One very potent example of this is the BlueScope Steelworks in Port Kembla [134-136]. In this instance the union of the New South Wales fire brigade refused to fight fires at the site due to the use of recycled water in the plant’s fire control system. Citing potential health effects a protracted industrial action was fought between the union and the New South Wales government, during which time the plant was provided with potable water, while recycled water was sent to ocean outfall. The union was requesting indexed death and disability benefits for financial protection if they became ill from using the water [137]. The issue was eventually solved by arbitration from the Industrial Relations Commission.

In general, employee concerns are going to be with the safety of the water. Keeping employees on side will require open and transparent communications from management particularly focusing on this issue. It should be remembered there are two primary health concerns in non-potable waters: trace compounds (e.g. endocrine disrupting compounds, hydrocarbons and pharmaceuticals) and pathogens (e.g. bacteria, viruses and protozoa). The use of non-potable water for irrigation limits exposure and ingestion and therefore leaves only infection from pathogens as a risk. Where rainwater or Class A recycled water is used, there is no significant risk as these waters are generally considered pathogen free or very close to. Storm water and Class B and C recycled waters will be disinfected, but should still be treated with caution and will require some controls and barriers.

When using non-potable water, a thorough communication strategy between management and the workforce should be enacted. This should encompass:

- Communicating exactly water the water is (both source and quality), where it will be used and what health controls are in place
- Explain how using non-potable water may change irrigation practises
- Determine and address worker concerns
- Explain procedures on reporting issues and how issues will be resolved during operation

Further ideas may be found in the Australian guidelines [5]. It is important that, at all times, communication is two way and open. This will ensure employees will feel confident that the changes made onsite will not affect them or their health.

2.2.7.3 Image

Although not strictly a business, local governments operate on a similar level and image is important in attracting local investment and increasing population. Since the growth in the environmental movement in the 1980s and 1990s environmental issues have become entrenched on the public agenda. Use of alternative water sources to maintain resources that are important to the public should help to improve the image of a local government area. Efforts should be made to highlight the environmental commitment of the council, stating specific local improvements, not just just generalised information. Possible benefits to consider are:

- More potable water now available for drinking
- Sporting fields and parks are drought-proofed for long term community enjoyment
- Decreased pollution loads at traditional discharge points such as sewage or stormwater outlets that will improve the quality of local creeks or beaches
- Maintaining groundwater levels preventing seawater intrusion or simply to ensure sustainable use of groundwater sources
- Reuse of a valuable public resource, reducing the ecological footprint.

Evidence suggests that businesses gain a competitive advantage from strong environmental performance [138]. It is possible that green councils may also do well at attracting these businesses and investment if their environmental image is equally high.

Another point to consider is recognition programs. These programs are useful to enter as the proponents will need to investigate what is being done and how it may be improved. Importantly these awards provide a free and positive marketing platform for the winners and the runners up regardless of their focus. Some of the awards of interest include:

A. savewater! Awards

(http://www.savewater.com.au/)

Identifies products, organisations and individuals who have demonstrated innovation and commitment to deliver efficient water usage.

B. Banksia Environmental Founation Award

(http://www.banksiafdn.com/)

The Banksia Foundation supports and recognises members of the community that have made a significant contribution to the environment. There is a water category that is awarded to an organisation that has enhanced or conserved freshwater and marine environments. There are also categories for climate (reducing greenhouse gas emissions) and sustainability (minimising the ecological footprint).

C. Premiers Sustainability Awards

(http://sustainabilityawards.vic.gov.au)

These awards recognise individuals and organisations that have made a substantial effort towards reducing their environmental impact.

D. Grow Me the Money

(http://www.growmethemoney.com.au)

This is a rewards program rather than awards. By joining the project and performing environmental initiatives, organisations can earn points. These points can be redeemed to obtain support from consultants, training and education and access to resource efficient products. The recognition program has four levels that can be used by members for 12 months. Increasing through the levels requires commitment to the program. The program will also help by providing intense media coverage of the efforts made by the members.

CHAPTER 3 – Water Sources

3.1 Introduction

An understanding of potential water sources is important to any irrigation manager. In times of water shortage this is especially so. In the previous chapter general water quality concerns were considered. In this chapter the individual water sources will be considered and most likely contaminants investigated. As such there will be some samples of water qualities for each water type. When looking at these qualities it is important to remember that water sources can vary considerably. Wherever possible this is highlighted. It is also important to keep in mind the quality of potable water as a comparison. This is shown in Table 3.1.

The following sections are structured in roughly the same way looking at general definitions of the water category, important quality issues, treatment techniques and advantages and disadvantage. Each of these is generally tailored to irrigation of sports fields.

3.2 Rain Water/Roofwater

3.2.1 Introduction

Rain water, or roof water, is used to refer to water that falls only on the roofs of houses or buildings. It is considered separately from stormwater as it is generally collected at the site of use and has not contacted surfaces that are generally perceived as polluted, such as roads and gardens. Rain water can be a common source of drinking water is some parts of Australia and is quite heavily used in irrigation of gardens in an urban environment. The National Guidelines for Water Recycling considers rain water as a source of irrigation water within Phase 2 [6]. The current understanding of rain water and issues associated with its use in irrigation are discussed below.

Table 3.1 Representative potable water qualities in the Greater Melbourne region.

Parameter	Units	City West Water [139]					Yarra Valley Water [140]		South East Water [141]				Barwon Water [142]	
		General			Altona	Footscray	Tullamarine	Broadmeadows	General			Dandenong	Lovely Banks	Highton
		Min	Max	Mean	Mean	Mean	Range	Range	Min	Max	Mean	Mean	Range	Range
Free Chlorine	$mg.L^{-1}$	0	0.85	0.1	0.05	0.06	0.01-0.45	0.02-0.28				0.09		
Alkalinity	$mg.L^{-1}$ as $CaCO_3$	10	13	12	11	11			12	18	15			
Aluminium	$mg.L^{-1}$	< 0.01	0.08	0.02	0.02	0.02			0.02	0.09	0.05		< 0.01 - 0.047	< 0.01 - 0.031
Ammonia	$mg.L^{-1}$								0.003	0.01	0.006			
Calcium	$mg.L^{-1}$	7.1	8.9	7.4	7.6	7.6			2.9	7.1	4.9			
Chloride	$mg.L^{-1}$	13	16	15.4	16	16			6	8	7			
Colour	Pt/Co (CWW, BW), HU (SEW)	< 2	7	2	2	2						5.9	< 1 - 20	< 1 - 19
Conductivity	$uS.cm^{-1}$	55	140	107	114	113			7	72	54			
Copper	$mg.L^{-1}$	< 0.004	0.032	0.008	< 0.004	0.015	0.004-0.140	0.011 - 0.150	0.002	0.66	0.04		0.003 - 0.17	0.004 - 0.07
Fluoride	$mg.L^{-1}$	0.7	1.08	0.9	0.9	0.9			0.61	1	0.88		0.07 - 0.1	0.07 - 0.09
Hardness	$mg.L^{-1}$ as $CaCO_3$	23	29	26	27	27	11 - 18	11 - 16	12	20	16		30 - 100	30 -37
Iron	$mg.L^{-1}$	< 0.02	0.24	0.02	0.02	0.02	0.03 - 0.17	0.03 - 0.12				0.06		
Magnesium	$mg.L^{-1}$	1.6	2	1.8	1.9	1.9			0.9	1.4	1.2			
Manganese	$mg.L^{-1}$	< 0.01	0.03	< 0.01	< 0.01	< 0.01			0.001	0.034	0.007		< 0.002 - 0.014	< 0.002 - 0.036
Nitrate	$mg.L^{-1}$	0.84	1.37	1.18	1.2	1.24			0.041	0.2	0.11			
pH	units	7	9.7	7.5	7.6	7.4	7.0 - 7.4	7.0 - 7.5				7.3	7.4 - 8.7	7.1 - 8.3
Potassium	$mg.L^{-1}$	1	1.2	1.1	1.1	1.1			0.6	0.8	0.7			
Silica	$mg.L^{-1}$	5.2	6	5.6	5.7	5.6			5.5	7.7	6.6			
Sodium	$mg.L^{-1}$	6.7	9.3	8.2	8.9	8.3			3.9	5.6	4.7			
Sulphate	$mg.L^{-1}$	7	12	10.5	11	12			1	2	2			
TOC	$mg.L^{-1}$	1.3	1.9	1.5	1.5	1.4			1	2	1.5			
Total Phosphorus	$mg.L^{-1}$	< 0.003	<0.003	0.003	< 0.003	< 0.003			0.006	0.09	0.016			
TDS	$mg.L^{-1}$	57	70	67	69	68			24	70	47			
Turbidity	NTU	0.1	9.6	0.6	0.4	0.5	0.50-1.20	0.40-1.40				0.6	< 0.1 - 4.6	< 0.1 - 1.1

3.2.2 Quality issues

3.2.2.1 Chemistry

Rainwater quality is generally very good with only low levels of the main constituents of concern. Typical qualities of water capture from a roof catchment are shown in Table 3.2. The good quality of the water can however, makes variations more pronounced. Studies have shown that different types of storms will result in different water qualities [143]. Ultimately this comes down to the location where the storm formed and areas where the storm passes. For example storms that form over the ocean will have higher salt contents in their water and are little influenced by atmospheric pollution [143]. On the other hand those that pass over desert regions will contain some minerals including magnesium, potassium and silicates [144, 145]. The presence of lightning in thunderstorms can also change the composition of rainwater, with pollutants more easily oxidised by the presence of ozone in the storm clouds ultimately leading to a more acidic rain [143]. While collected materials during storm formation and movement will account for some ionic loading, another significant source is "wash out", that is the collection of atmospheric pollutants while the rain is falling. This can result in acidity in rainwater (like the acid rain phenomena) [143], increased salinity from sea spray [146], and metals from fossil-fuel burning [97]. Prediction of rainwater quality based on location is difficult but should consider the following:

- **Distance to salt water/ocean**: Sodium and chloride concentration in rainwater are generally due entirely to dissolved sea spray [144]. The distance from a salt water source appears to correlate to the contents of these two ions [97, 146]. Predominant wind direction is also a contributing factor with sea-based winds contributing greater salt loading than land-based [97]. The concentration of chloride ions in rainwater have been reported in the range of 0.4 and 3000 $mg.L^{-1}$ in the past [146]. If the sodium content matches or is similar to this it cannot always be assumed that collected rainwater is suitable for irrigation. It should be noted however, that the upper concentration reported above is extreme. Concentrations of strontium, magnesium, rubidium and potassium may also be elevated as a result of sea spray.
- **Location near major industrial emission sites**: Heavy industrial sites and heavy large vehicles use can result in elevated metals contents. Previous studies in Newcastle, New South Wales have shown increases in As, Cd, Cr, Co, Cu, Fe, P, Pb, Mn, Se and Zn content in rainwater associated with heavy diesel traffic nearby [146]. In general these were not believed to have increased beyond legal limits. Acidity or pH on the other hand does not correlate well with fossil fuel burning. Studies in both Newcastle [97] and the Latrobe Valley in Victoria [147] have been unable to see any trend with pH as a function with distance from industrial sources of NO_x and SO_x gases, in contrast to studies in the Northern hemisphere [143]. It has also been suggested that local cement works can contribute elevated levels of calcium, silica and sulphur to rainwater, although this has not been conclusively proven [148].
- **Time since previous storm event**: Though not obviously related to location, the collection of pollutants and dust in the atmosphere and on the surface of the roof can result in increased contamination once a storm arrives. If a rainwater collection system is established in an area with high occurrence of short storm events followed by long dry spells this should be taken into account.

Table 3.2 General roof water tank water qualities

Component	Global Average [149]	Newcastle, Tank [150]	Newcastle, Tank, Coastal[1] [97]	Newcastle, Tank, Inland[1] [97]
Ammonia ($mg.L^{-1}$)		0.2		
Barium ($mg.L^{-1}$)			0.009634	0.005
Cadmium ($mg.L^{-1}$)	0.00066	< 0.002	0.00023	0.00009
Calcium ($mg.L^{-1}$)		1.19		
Chloride ($mg.L^{-1}$)		6.65		
Chromium ($mg.L^{-1}$)			0.00014	0.00004
Copper ($mg.L^{-1}$)	0.061		0.342	0.00088
HPC ($cfu.mL^{-1}$)		10		
Iron ($mg.L^{-1}$)		0.06	0.428	0.00333
Lead ($mg.L^{-1}$)	0.054	< 0.01	0.0127	0.00582
Magnesium ($mg.L^{-1}$)			2.11	0.43
Manganese ($mg.L^{-1}$)			0.0706	0.0112
Nitrate ($mg.L^{-1}$)		0.05		
Nitrite ($mg.L^{-1}$)		1.3		
pH	5.7	6		
Potassium ($mg.L^{-1}$)			4.24	0.343
Pseudomonas spp. ($cfu.100mL^{-1}$)		110		
Sodium ($mg.L^{-1}$)		4.03	13.2	3.53
Strontium ($mg.L^{-1}$)			0.0209	0.00257
Sulphate ($mg.L^{-1}$)		2.16		
TDS ($mg.L^{-1}$)		105		
TP ($mg.L^{-1}$)	0.15		0.0933	0.0407
TSS ($mg.L^{-1}$)	47	97.55		
Turbidity (NTU)	9.1			
Zinc ($mg.L^{-1}$)	10.2 (Zn-based roof) 0.34 (Non-Zn roof)		0.875	0.166

1. These two samples were summertime sample and were significantly different from winter samples.

Once rain hits a roof, additional sources of contamination must be considered. One point of local variation is materials that deposit on the roof. Sea salt may contribute more salt to the water at this point as can local soil/dust materials. Importantly local industrial activities may impact on the site from dust or aerosol emissions. There is a common held belief that discarding the "first flush" or rainwater will minimise this, however this principle does not hold for all potential contaminants [118] and the national guidelines do not recommend this [6]. Despite this short rain events have been shown to result in spikes in the conductivity of water collected in rain tanks that are not seen in sustained rain events [97]. Some wash off of contaminants should be assumed to occur, however with the generally high quality of water collected, this may not be a concern.

The construction material on the roof, tank and piping is one of the more important things to consider when collecting rainwater for irrigation use. A number of studies have shown elevated levels of a number of metals, often exceeding drinking water guidelines [97, 151]. This comes about due primarily to corrosion and leaching. Galvanised steels and irons as roofing and tank materials are of particular concern showing elevated levels of zinc [96] that can be a potential threat to turf. Copper piping and fittings are also a concern with studies showing concentrations of copper 380 times greater than sites without these [97]. These two in particular are of concern, according to the Australian Guidelines, when irrigation is the end use [6], although other studies have shown elevated levels of lead, iron, cadmium, manganese, aluminium [96] and nickel [97]. Levels potentially in breach of guidelines have been reported for cadmium, iron and zinc in one Australian study [151] and lead and iron in another [97]. In the second case this occurred during summer when elevated temperatures may also accelerate corrosion processes. Importantly, studies investigating compliance with the national recycled water guidelines have shown aluminium, iron, lead and zinc levels were exceeded on some occasions [152]. Zinc concentrations in particular were elevated with levels as high as 11.5 $mg.L^{-1}$ recorded at one site. The Australian Guidelines for Water Recycling generally recommends against direct use of rainwater harvested from galvanised roofs in irrigation and suggest limiting irrigation to 300 $mm.yr^{-1}$ where this cannot be avoided [6].

Maintenance practices on roof catchments are also important. Build-up of leaf matter on rooves can lead to increased corrosion rates and biological growth due to the stagnation and ponding of water. Importantly, it is also possible to leach tannins and other compounds from the leaves that will lead to a discolouration of the water [97] and potential increase in toxic components. This may not lead to an issue with turf quality, but can impact user’s perceptions of the water. The Australian Guidelines for Water Recycling recommend using roof spaces with no overhanging branches. Where this is unavoidable, regular (2 weeks to monthly) inspection and cleaning of roofs that are being used to collect rainwater are vital to the efficient running of the system.

Water quality is also dependent on the tank’s residence time, or the amount of time the water takes to pass through the tank. Studies have shown that rainwater pH is dependent on the amount of time it is stored for with the pH dropping over time [97]. Using water quickly should allow water to maintain a pH of 5-6.

3.2.2.2 Biology

The biological risks of rainwater use come primarily from the ecology of the storage tank. Here, long residence times and near-stagnant water can provide an environment that encourages the growth of micro-organisms. The roof, on the other hand is generally a hostile environment to micro-organisms. High temperatures and significant UV irradiation should impact on microbial populations [153]. Unless ponding or pooling of water occurs, bacteria should only be able to wash into a rainwater tank if they have reached the roof during or just prior to rain. In general there are two pathways bacteria may enter a rainwater tank: animal sources and airborne/dustborne bacteria [94].

Until recently, animal sources, particular faecal matter, were believed to be the primary source of microbial contamination of rainwater. Birds and possums are typically nominated as a source of enteric bacteria that are potentially harmful to humans. The Australian Guidelines for Recycled Water focus on pathways to reduce this risk such as ensuring there are minimal branches and other objects overhanging a roof [5]. This has the added benefit of reducing the possibility of a build-up of leaves on the roof space. Where these guidelines are followed there is generally minimal problems from contamination by enteric bacteria and log reduction requirements are minimal for irrigation as an end use.

Of potentially greater significance is the entry of other bacteria that are not enteric. Studies of Australian rainwater tanks from the east coast have shown significant bacterial contamination [94]. These non-enteric bacteria significantly outnumber their enteric counterparts, suggesting that coliform or *E. coli* counts may not be sufficient for determining potential health impacts from water [94]. Their spread appears to be dependent primarily of local wind strength and direction, with stronger winds resulting in higher bacterial counts [153]. The species that are most prevalent include *Acidovorax*, *Hydrogenaphaga*, *Polaromonas*, *Variovorax* and *Pseudomonas* spp. [94]. Not all these bacteria are necessarily dangerous to human health, but some, such as *Pseudomonas*, can exacerbate skin conditions. Some other pathogens, such as *Klebsiella* and *Legionella*, are also of concern due to their ease of spread and ability to cause infection from aerosols. It should be noted however that only *Klebsiella* has been identified in rainwater tank in Australia to date and this was in significant numbers [94]. To minimise human health impacts from rainwater some disinfection should be performed.

Another important consideration is the theory that the ecosystem that establishes in rainwater tanks is actually beneficial to water quality. It seems likely that the bacteria commonly found in rainwater tanks are better adapted to these conditions and can out compete enteric bacteria keeping their numbers low [94]. It has also been shown that water quality improves as it passes through the tank [150]. These two observations are of importance as it implies that disinfection of water in the tank could actually be detrimental to water quality and suggests that disinfection should occur outside the tank as water is removed using techniques such as ozonation or UV irradiation [94].

3.2.3 Treatment

In general rainwater should not require ant treatment before use in irrigation. This view has been supported in the Australian Guidelines for Water Recycling [6]. With this in mind, some researchers believe that the microbes that survive in a water tank may need to be eliminated before use [94]. Where this is the case, the effectiveness of these microbes in improving water quality and reducing the numbers of enteric bacteria suggests that full tank disinfection is not advisable [94]. Instead in-line disinfection just prior to use utilizing either ozonation or UV disinfection may be the preferred option.

3.2.4 Inherent Benefits

Rainwater is the most pure recycled water meaning it is suitable for irrigation without significant treatment. This means there is minimal capital outlay, very small space requirements and very few ongoing costs. In terms of energy requirements rainwater relies on energy only for pumping and potentially for disinfection. These requirements will be common across all alternative waters and suggest that the carbon footprint should be least for rainwater.

The other significant benefit of rainwater is the legal issue of water rights. It is generally assumed that rain falling on a roof within a property boundary can be used by the property owner. Agreements with other property owners can complicate this issue somewhat, however it is clearer than other water sources such as stormwater and sewer mining.

3.2.5 Potential Disadvantages

While rainwater is a sustainable water source it is still climate sensitive. Periods of drought and low rainfall, the time period when a turf will require significant irrigation, will mean little water is available from this source. The size of the catchment (i.e. the amount of roof space available) and the size of the storage tank dictate the amount of water that will be made available. With this in mind it is unlikely that roofwater could serve as the only source of irrigation water for a water hungry turf and another source would be required to complement it and help make up any shortfall.

3.2.6 Conclusions

Rain water as a relatively clean water source should be usable without treatment for irrigation. While care should be taken to reduce the impact of dissolution of galvanised metals, copper and lead, the water can still be used for irrigation with careful monitoring. While it will suffer in terms of water availability during times of drought, it is generally an inexpensive and simple way of meeting at least some of the irrigation requirement of a sports field.

3.3 Stormwater

3.3.1 Introduction

Stormwater is the rain water collected, generally across a large area, from practically all surfaces within a catchment. This means the water has come into contact with sources typically seen as contaminated such as roads, footpaths, gardens and open space. It generally is slightly lower in quality than roof water, however it is also available in larger volumes.

Unlike roofwater, stormwater does not become immediately available once rain starts to fall. Surfaces can act as filters to slow down the flow of water, particularly where the surface is pervious. Also, it cannot be assumed that all water that falls in a catchment will be available. While the water from roofs, roads and pavements that are directed towards collection systems will generally become available quickly, runoff from surfaces such as gardens, open space and bushland will be partially retained and retarded by the surfaces reach a collections point significantly slower, with flows sometimes arriving days after a significant rainfall event. This makes modelling and designing treatment systems and irrigation systems that rely upon them more difficult.

3.3.2 Quality Issues

Though it is sourced primarily from rain water, stormwater is typically of a poorer quality due to the pollutants that are collected in wash out from surfaces. Unlike roofwater, stormwater is affected more by the catchment than storm-based impacts. In determining the suitability of stormwater or treatment that may be required, the characterization of the catchment must be considered.

A detailed discussion on rain water harvested from roofs is provided in Section 3.2. Briefly, the main concerns are the material the roof and collection system (down-pipes etc.) are made from. Copper-based products and galvanised irons and steels will contribute significantly to zinc and copper concentrations [96, 97], while lead from lead flashing on tile roofs can also be significant [152]. Importantly, there is definitely less (more likely no) control over the maintenance of roofs that could lead to increased bacterial loads. There would also be no control of roofs that may have exhausts (such as chimneys or heating exhausts, air conditioning units, exhausts from industrial or laboratory process). These may contribute greater loadings of some toxic chemicals, specifically metals and organic compounds, as well as opportunistic bacteria such as *legionella* where evaporative air conditioners are not well maintained. Disinfection should always be employed in storm water treatment.

The walls of houses will also contribute to the chemical loading of stormwater. The main points of interest are zinc from painted walls, copper from bricks [154] and wood preservative from various sources [155]. In general, both of these contaminants are associated with wooden or weatherboard walls and are only of interest where there are a large number of dwellings made from these materials in a catchment.

Pavements including footpaths and courtyards will contribute mainly to the calcium loading of stormwater [156]. Alkalinity (CO_3^{2-} concentrations) also increases on concrete pavements [118]. Calcium, either from erosion or dissolution of concrete and cement, will typically be present in higher concentrations than sodium salts. Typical concentrations for important species are shown in Table 3.3.

The contribution from roads will vary significantly depending on the level of traffic [157], the composition of the traffic [97] and the material of the road. Concrete surfaces will contribute more calcium and alkalinity as noted previously [118, 156]. Residuals from diesel combustion including arsenic, beryllium, cadmium, chromium, cobalt, lead, manganese, silicon and selenium will be more common where heavy vehicles are common [97] while zinc and copper from tyres and brakes respectively [154] are believed to be related to traffic densities. Polyaromatic hydrocarbons are also related to traffic densities as a residual of fuel combustion. Interesting, the levels of phosphorus and nitrogen correlate to decreasing traffic density [149]. This is believed to be due to vegetation encroaching on roads with low traffic volumes and contributing to the runoff. Where deicing is employed these salts (typically sodium or calcium based) will contribute significant quantities to stormwater. Examples of road runoff qualities are shown in Table 3.3.

From residential catchments the other major contributor are gardens and open space. Typically these will result in higher concentrations of phosphates and nitrogen compounds due to the heavy use of fertilizers [149]. This increased level of nutrients typically is reason for stormwater treatment prior to it being discharged to a watercourse. Gardens and open space may also contribute to higher salt loadings from these compounds. Pesticides and herbicides will also be present in runoff from these areas. If the contribution from these surfaces is high then it will be particularly detrimental to irrigation and treatment to remove these compounds will be necessary.

Table 3.3 Typical stormwater runoff qualities from different surfaces.

Parameter	Roads [157]	Pavement [156]	Roofs [150]	Garden [158]	Petrol Station [159]	Auto Dismantler [159]
Ammonia ($mg.L^{-1}$)		0.5	0.19			
Arsenic ($mg.L^{-1}$)	0.0084					
Cadmium ($mg.L^{-1}$)	0.0009		< 0.002			0.0005
Calcium ($mg.L^{-1}$)	12.7	12.16	2.45			
Chemical Oxygen Demand ($mg.L^{-1}$)	49.5	14.2			310	634
Chloride ($mg.L^{-1}$)		3.64	12.1			
Chromium ($mg.L^{-1}$)	0.0088					0.0059
Conductivity (us.cm-1)		72.48				
Copper ($mg.L^{-1}$)	0.0513			0.08	0.0781	0.0638
Fecal coliforms	6083 $MPN.100mL^{-1}$		218 $cfu.100mL^{-1}$			
Glyphosphate (pesticide, $mg.L^{-1}$)	27.8					
Lead ($mg.L^{-1}$)	0.0796		0.014	0.045	0.0028	0.0296
Magnesium ($mg.L^{-1}$)	3.2	0.8				
Nickel ($mg.L^{-1}$)	0.0101					0.0248
Nitrate ($mg.L^{-1}$)	1.1	0.721	0.23			

Table 3.3 cont Typical stormwater runoff qualities from different surfaces.

Parameter	Roads [157]	Pavement [156]	Roofs [150]	Garden [158]	Petrol Station [159]	Auto Dismantler [159]
Nitrite ($mg.L^{-1}$)	0.1	0.086	1.16			
Oil and Grease ($mg.L^{-1}$)	10.6					
pH	7.3		5.65			
Sodium ($mg.L^{-1}$)	11	2.85	8.4			
Sulphate ($mg.L^{-1}$)	4.2	6.44	6.79			
Total coliform	21970 $MPN.100mL^{-1}$		542 $cfu.100mL^{-1}$			
Total Dissolved Solids ($mg.L^{-1}$)	184.1		97.9			
Total Hydrocarbons ($mg.L^{-1}$)					1.2	12
Total Kjeldahl Nitrogen ($mg.L^{-1}$)	2					
Total Nitrogen ($mg.L^{-1}$)		2.15		0.9		
Total Organic Carbon ($mg.L^{-1}$)		4.42				
Total Phosphorus ($mg.L^{-1}$)	0.3	0.114				
Total Suspended Solids ($mg.L^{-1}$)	148.1		4.94		125	378
Turbidity (NTU)	310.1					
Zinc ($mg.L^{-1}$)	0.2034			0.22	0.3784	0.2838

Bushland will contribute probably the least contaminated water of all runoff sources. In forested areas, phosphorus and nitrogen compounds are effectively filtered by the vegetation and without the heavy use of fertilizers contribution from these compounds is quite low [149]. Leached salts and organics from leaf litter are also quite low [160].

Industrial sites are generally considered to be detrimental to water quality in a catchment area. They can contribute high loadings of potentially unknown or unexpected compounds. Having said this, larger industrial sites would be required by the Environmental Protection Agency to capture all rainwater from the site for treatment prior to disposal and only smaller sites are likely to contribute. While these are often easy to separate from residential catchments, some like petrol stations and auto works are often present within residential catchments. A study by Gnecco and co-workers [161] has shown increased levels of suspended solids and hydrocarbons from such sites. The auto dismantled in particular saw elevated levels of these compounds as well as metals zinc, copper and lead.

The concept of first flush and removal of a small volume of stormwater collected at the beginning of a storm is a well known concept in recycling. First flush is essentially defined as the initial period of a storm event where the mean concentration during the period significantly exceeds the event mean concentration. However, there are significant questions that have been raised over the applicability of the first flush concept to all contaminants. While some compounds show definite effects of first flush, others show no significant difference in concentration over time [118, 161]. It is believed that this is due to larger particulates that require larger volumes to be dislodged or released [118]. Regardless, removal of the first flush in not recommended by the Australian Guidelines as an effective technique for decreasing contaminant loads [5].

Stormwater base flow comes as a contribution from ground water or excess moisture in the surrounding soil. It will often be of high mineral content, but could also contain local contaminants from the water table. An understanding of pollutants may have entered the water table will be of importance where infiltration into the storm water system is high. Sea water infiltration may also be a possibility at coastal sites where groundwater have been over-abstracted.

Biological contamination will come in two main forms, enteric bacteria and viruses primarily from faecal sources and opportunistic bacteria that are present almost everywhere. A major point source for enteric bacteria will be sewage treatment plants (STPs). The Australian Guidelines for Recycled Water strongly recommends that STPs not be present in stormwater catchments being used to generate recycled water [5]. Non-point sources will include faecal matter from pets and other animals in the area and generally cannot be avoided. Opportunistic bacteria are also a concern due to the common use of aerosols during irrigation and the general potential for human involvement in the irrigation process. Potentially lethal species such as *legionella* and *klebsiella* may be present in storm water and skin irritants including the *Pseudomonas* species are known to dominate in rain water tanks [94]. Treatment to reduce and remove biological contamination will always be necessary when looking to reuse stormwater.

3.3.3 Treatment

The first step towards "treatment" or improvement of stormwater quality actually comes within the catchment. There are a number of steps that may be taken to partially treat, or at least improve the quality of, storm water as it passes into and through the stormwater collection system. Where performed correctly, street sweeping helps remove metals and particulates that have deposited on the roads and in gutters and ultimately reduces the impact of "first flush" (the higher concentrations of some species seen in the early stages of stormwater collection).

Pretreatment processes focus on the removal of large contaminants such as litter (both natural and artificial) and large particulate matter that will interfere in downstream processing. On a small scale this can be performed using litter baskets or baffled pits to separate litter. It can also be performed on a large scale using trash racks or gross pollutant trap [162]. Please refer to the necessary guidelines for more information on these techniques [162].

Swales and bioretention swales can be built into the side or median strip of a road to provide some pretreatment for stormwater [162]. The swale itself is a vegetated depression that can help retard water flows and allows for some basic sedimentation of coarse particles. Bioretention uses a filter medium (typically a fine soil such as sandy loam or coarse sand) to provide further filtration. The most important component however is the presence of plants growing in the medium that helps slow water movement and establishes a biofilm that can help in the biological treatment of water removing some pollutants and nutrients. The design of these systems depends partially on the characteristics of the area and what is needed in terms of treatment of pretreatment. The aim of swales in general is to provide some retardation of water flows and they are generally designed with this in mind. Otherwise they may be used as a technique to provide some treatment prior to aquifer storage or as part of a conveyance system. Design considerations can be found in documents from the CSIRO [162, 163].

Probably the most common form of treatment for stormwater is wetlands-based treatments. These are used to mimic natural environments and primarily focus on removing suspended solids, nutrients, and to a lesser extent organics, from stormwater. A wetland treatment system consists of at least two (generally three) main areas [98]. The first in the inlet zone, which will be a deep water pond to collect particles in the size range of sand and silt [98]. This area is generally permanently inundated. The second zone is the macrophyte zone. This is the area that is highly vegetated and should undergo periods of flooding and drying. This area will remove some of the finer particles and soluble pollutants through physical and biological means. It is very important that this zone undergoes regular drying and is not permanently inundated as this is how macrophyte zones exist naturally, and ensures that the wetlands operate at maximum efficiency.

These two zones are all that is needed for stormwater treatment, however a second deep water area is often added to increase the residence time of water passing through the system and encourage some further water treatment. This zone may also act as a permanent storage area from which treated stormwater could be effectively collected. Recommendations from the CRC for Catchment Hydrology in Australia recommend using a riser (a partially permeable wall that allows slow flow of water down to a preset storage height) to standardise the retention time throughout the process [98]. In general the riser should maintain a permanent storage of between 10 and 15% of the total storage. This allows for regular drainage of the macrophyte zone and best performance from the system. For more information on design practices for wetlands treatment please refer to the following reports and guidelines:

- *Water Sensitive Urban Design Engineering Procedures: Stormwater* (CSIRO Publishing) [163]
- *Urban Stormwater: Best Practice Environmental Management Guidelines* (CSIRO Publishing) [162]
- *Managing Urban Stormwater Using Constructed Wetlands* (CRC for Catchment Hydrology) [98]

The storage of recycled stormwater from wetlands treatment can lead to potential problems from potential water degradation by native wildlife. Generally native wildlife is encouraged to wetlands areas as they can assist in the processes that occur and keep nuisance species, such as snakes and mosquitoes to a minimum. Large quantities of local wildlife can however lead to degradation in water quality particularly nutrients and this should be considered when designing a storage system.

Pond detention is also used in stormwater treatment, but it is not necessarily as efficient. Generally ponds with longer retention times would be required to ensure the same pollutant removal efficiencies [98].

Natural processes rely heavily on the microbial breakdown of nutrients and organics in a water stream. Two of the important processes are nitrification and denitrification. These two processes are the backbone of biological nutrient removal. Nitrification ultimately is the process of oxidising ammonia to nitrite and nitrate, while denitrification reduces nitrate to nitrogen gas. The concern in stormwater treatment comes from the production of the greenhouse gas nitrous oxide N_2O (during both the nitrification and denitrification processes [164]) in much larger concentrations than seen in natural wetlands [165, 166]. Nitrous oxide has a greenhouse gas potential 296 times higher than carbon dioxide [167] and is a significant concern in wastewater treatment. The potential impact of N_2O and it formation should be considered as part of any stormwater treatment process.

The other greenhouse gas concern comes from the breakdown of organic pollutants in stormwater and naturally occurring in the wetland. Deep water tends to be low in oxygen and leads to the formation of anoxic zones in both the water and the soil where microbial populations tend to produce methane when breaking down organics [167]. Shallow waters have higher oxygen concentrations, and when dry reoxygenate the soil, resulting in aerobic microbes breaking organic compounds down to carbon dioxide. Methane has a greater greenhouse gas effect than carbon dioxide (about 23 times greater on a mass basis [167]).

Other means of treatment tend to focus solely on particulate removal [163]. In this respect sand filtration is the more common treatment technique [162]. This will remove particulate forms of metals and nutrients, and may help bind some phosphates, but unless slow sand filtration is employed (this technique also has a biological component), there will be no significant reduction. Whether metals exist in a solid or soluble form depends very much on the catchment characteristics. One of the more important properties is the pH that can be easily altered by the presence of different surfaces. Concrete and cement tend to result in a significant increase in pH due to the dissolution of alkaline materials in the cement [118]. Asphalt on the other hand does not alter the pH as dramatically (it is still slightly acidic) and consequently results in a different partitioning of metals between solid and dissolved forms.

3.3.4 Inherent Advantages

While stormwater is climate sensitive, the large catchment areas typically employed means they represent a significant water source under most circumstances. While it may contain significant levels of pollutants, it can also be a source of nutrients for irrigation water. Diversion of some of this water to irrigation will help to reduce pollutant loads in local water courses. Importantly, increasing demands by the Environmental Protection Agency may mean this water needs treatment prior to bay-side or watercourse discharge. This means that some of the treatment that may be necessary for stormwater recycling could already be in place. On the other hand, providing treatment for stormwater recycling will have the added bonus of reducing pollutant loads from discharged stormwater.

3.3.5 Potential Disadvantages

One of the biggest disadvantages to stormwater recycling is its general dependence on rainfall. While base flow will be present its contribution may not e particularly significant. This is important to treatment processes particularly those that rely on biological processes. These typically require relatively regular flows (i.e. rainfall distributed evenly across the year) or the technique can actually release more nutrients. This has particularly been seen in poorly designed wetlands and reed-bed treatments [168]. Wetlands treatment in Adelaide utilizes groundwater to provide flows to the wetland where stormwater supply is insufficient [100]. This, or some similar arrangement, should be established as part of the planning of a wetlands treatment scheme. The impact of evaporation on water storage and within wetland treatment systems also has the potential to concentrate nutrients deliberately being withheld from rivers and other watercourses. Specifically this can lead to cyanobacterial blooms. Water that has been contaminated with cyanobacteria cannot be used for irrigation due to the significant health risks posed. Such cyanobacterial blooms have been witnessed in stormwater treatment systems in the Greater Melbourne area over the past few years. Algae, while not presenting a human health risk, may result in chemical changes in the water, such as introducing surfactant, which can be detrimental to the microbiology in the soil associated with nutrient transformation and ultimately turf grass health.

The potential impacts of stormwater use are probably also the least understood. Most research to date has focused on other water sources for reuse, while stormwater research is more heavily focused on reducing nutrient loads in receiving waters. While more studies are starting to become available a greater understanding of micropollutants (i.e. pollutants that are present in very low concentrations)

3.3.6 Conclusions

Storm water can be a useful water source with a moderate to high level of nutrients that can be made available during irrigation. While its direct reuse is generally not possible without clear procedures to manage potential microbial issues, treatment can be cheap and effective. The treatment comes with the added benefit of reducing nutrient loads in discharges to sensitive water courses. The larger catchments typically mean stormwater could probably provide the irrigation requirement for a sports field or come very close. However it is still a climate sensitive water source, and drought or prolonged dry spells could negatively impact on the operation of some treatment techniques. Plans should made to combat this situation should it arise.

3.4 Recycled Water (Grey Water)

3.4.1 Introduction

Grey water refers to wastewater collected from around homes excluding water used in the toilet. The exclusion of toilet water is designed to reduce biological loads in the water and hence decrease the treatment (and often oversight) necessary in full black water recycling systems. This makes grey water reuse quite attractive in new developments, particularly for irrigation purposes. In larger sportsgrounds which may include shower blocks and canteens or kitchens the flows from this type of water may make it of interest. Decentralized treatment systems that separate toilet water from other residential wastewater may be possible, however they are unlikely to be feasible when full decentralized treatment of black water is also an option. With this in mind, the following discussion of grey water use may be of relevance only to fields with greater levels of associated infrastructure.

3.4.2 Quality Issues

3.4.2.1 Chemical

Untreated grey water qualities rely partially on the process from which they are sourced. Grey water may come from bathrooms (showers and hand-washing facilities), laundries and kitchens. Table 3.4 shows the water qualities associated with grey water sources from different parts of the home. This data is generally sourced from Australia and can be combined to give a rough guide of water quality from larger facilities. Variations in qualities do occur largely due to the products used, but also due to water saving initiatives that, while not necessarily impacting loadings, do result in concentration increases due to lower water flows.

Table 3.4 Typical water qualities for grey water from different household processes.

Component	Source							
	Washing Machine [169]	Dish Washer [169]	Shower [169]	Kitchen Sink [169]	Vanity Unit [169]	Toilet Block [169]	Bathroom [170]	Laundry [170]
Alkalinity (mg.L^{-1} as a $CaCO_3$)							19-60	19-220
Aluminium (mg.L^{-1})	1.91	0.27	0.37	0.09	0.27	0.08	< 1.0 - 1.4	< 1.0 - 44
Boron (mg.L^{-1})	< 0.02	< 0.02	< 0.02	< 0.02	< 0.02	0.09	< 0.1	< 0.1 - 0.6
Cadmium (mg.L^{-1})	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 1	< 0.01 - 0.05	< 0.01 - 0.05
Calcium (mg.L^{-1})	7.17	11.73	7.68	8.73	83.59	15.46	2.7 - 8.6	2.3 - 12
Chromium (µg.L^{-1})	< 5	< 5	< 5	< 5	< 5	< 2		
Cobalt (µg.L^{-1})	< 5	< 5	< 5	< 5	< 5	1.08		
Copper (mg.L^{-1})	0.17	0.811	0.121	0.268	1.39	0.471	< 0.05 - 0.32	< 0.05 - 0.49
Fluoride (mg.L^{-1})	0.995	0.992	0.76	0.844	1.4	< 0.1		
Iron (mg.L^{-1})	0.09	0.121	0.11	0.146	0.19	0.546	< 0.05 - 8.0	< 0.05 - 4.2
Lead (mg.L^{-1})	0.5	0.56	< 0.01	0	0.03	0.0046	< 0.05	< 0.05 - 0.48
Magnesium (mg.L^{-1})	1.47	1.628	2.132	2.631	2.4	5.58	1.2 - 2.3	0.7 - 5.3
Manganese (mg.L^{-1})	< 0.0002	< 0.0002	< 0.0002	< 0.0002	< 0.0002	< 0.1		
Molybdenum (mg.L^{-1})	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005	2.61		
Nickel (mg.L^{-1})	0.0016	0.032	< 0.003	< 0.003	< 0.003	< 0.003		
Oil and Grease (mg.L^{-1})							10 - 180	8.0 - 170
pH							6.4 - 8.1	6.3 - 9.5
Potassium (mg.L^{-1})	5.8	13.23	< 0.01	11.8	5.4	92.08	1.3 - 5.2	1.1 - 23
Sodium (mg.L^{-1})	116.6	260.6	13.47	40.1	26	87.23	7.4 - 29	12 - 480
Suspended Solids (mg.L^{-1})							34 - 380	26 - 400
Total Dissolved Solids (mg.L^{-1})							52.5 - 160	53 - 563
Total Kjeldahl Nitrogen (mg.L^{-1})	5.45	16.7	5.02	10.9	13.34	276.7	2.4 - 23	1.0 - 40
Total Phosphorus (mg.L^{-1})	0.22	12.18	0.26	2.2	64	50.06	0.1 - 0.88	0.062 - 42
Zinc (mg.L^{-1})	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.2	0.13 - 13	0.1 – 11

Bathroom

Water from the bathroom will typically have a high sodium concentration due to the sodium content of soaps and other personal care products [95]. Cleaning products such as bleaches will also contribute to the load of sodium from these areas. Of greater interest, particularly at sportsfields, could be the loadings of zinc that are attributed to the washing off of sunscreen in the shower and with hand-washing [95], however zinc concentrations generated in grey water in a typical home are similar to the incoming tap water [169].

The type of soap used will also impact on water quality, with solids soaps contributing more solids and organic content than liquid soaps [171]. Different soaps may also impact on the salt concentrations/loadings in the final water quality. Toothpastes and metal abrasion from electric toothbrushes do contribute measurable quantities of metals to grey water, however they are not particularly significant [172]. Oil and grease loadings from bathrooms are also quite significant representing half of loadings found from a house [173].

Kitchen

Food scraps and dishwashing contribute significant loads of nutrients, some metals (such as zinc) [169] and significant quantities of oil and grease (roughly a third of all oil and grease from grey water) [173]. Poor water quality (high nutrients and grease and oils) is often a justification for the exclusion of kitchen wastewater from grey water recycling systems [174]. Detergents can contribute significant sodium content and some contain high levels of phosphates [169]. Low phosphate detergents are available, however anecdotally these are not seen to give as good a clean in dishwashers and there is some opposition to their use.

Investigations into the use of untreated kitchen grey water for long-term irrigation in Israel, specifically investigating the impact of oil and grease of irrigated soils have found significant concentrations of oil and grease in the top 20 cm of soil [113]. However, the soil did not show any significant water repellence. It was theorised this was due to the additional presence of surfactants that may have acted as a bridge, limiting the hydrophobic impact of the oils.

Laundry

Grey water from laundries can be variable in quality and daily quantity as clothes washes are not necessarily performed regularly, but only when a load is generated. The main contamination of the water comes from the materials accumulated on clothes. In terms of product choices, laundry powders contribute greater salt loadings than liquids [95] and front-loaders contribute higher nitrogen and suspended solids concentrations than top-loaders [95]. Some laundry detergents may use significant levels of phosphates, however this is decreasing over time as reformulations occur [95]. Similarly historically high levels of boron in grey water from detergents [16, 170] have now been all but eliminated [169].

3.4.2.2 Biology

Biological contamination of grey water comes from two main sources: faecal contamination and contamination from food. Faecal contamination comes primarily from laundering of contaminated clothing (nappies etc.) and from showering [175].

Contamination from food focuses on bacterial species such as *Campylobacter* and *Salmonella* [176]. These are enteric pathogens that may be ingested as part of aerosolized irrigation water. Contamination of grey water may come from the cleaning of food preparation surface and the cleaning of towels used for this purpose. Cross contamination is common where only detergent and water are used to clean [177]. Disinfecting surface using sodium hypochlorite solutions (bleach) has been shown to decrease the presence of bacterial species more effectively [177] and may lead to lesser contamination in grey water. However, even with reduction, regrowth is still possible.

The high nutrient and organic loads that can occur in grey water and potentially elevated temperatures depending on dominant sources encourages the growth of bacteria in grey water storages and treatment systems prior to disinfection [174]. The risk of regrowth and particularly the level of viruses, imposes the need for disinfection of grey water [175].

3.4.3 Treatment

There are a large range of available techniques available for the treatment of grey water streams [174]. The treatments can be quite similar to those used in sewage treatment, although the demands on them are not necessarily as high. As such they can be divided into three processes: physical treatment, biological treatment and disinfection.

Pre-treatment is an important part of any grey water treatment system. Here large solids (e.g. food scraps) are removed and the oil and grease content can be reduced [174]. Pre-treatment may use very coarse filters or screens, but can also use a septic tank [174] where large solids settle and insoluble oil and grease float to the surface. Further microbial processes may also occur here depending on the residence time.

Physical treatments typically involve either allowing particulate matter to settle from the wastewater stream, or using a filtration to separate particles. At the less expensive end of the treatment processes are the sand and soil filters. The generally coarse nature of sand used for and filtration will remove significant fine particulate matter and some oil and grease from a wastewater stream at a relatively fast rate. Soil filtration on the other hand occurs much more slowly, however this means the biofilms can form and instigates some biological treatment as well as filtration [174]. This means that the nitrogen content of the water can be significantly reduced [178]. Also, the nature of soil means that entrapment of phosphates is far more effective than in sand filters and significant total phosphorus reductions can be achieved [178].

Settling can be inexpensive, however it is typically supplemented by chemical coagulation and flocculation which can add significantly to the expense. The focus again is on physical removal of particulates and some organic matter. The total phosphorus and total nitrogen contents are largely unaffected and the nutrient value of the water typically remains [174].

The other class of physical treatment revolve around membranes. Ultrafiltration is typically used to remove particulates and some organic matter from the water, while retaining high levels of nutrients [179]. One decentralized grey water plant in Germany utilized this technique specifically to generate water for irrigation [179]. Other membrane filtration techniques such as reverse osmosis can also be used. RO is able to effectively remove salts where this is a concern, however it is very energy intensive and ultimately expensive to run [180].

Biological treatments are also used in grey water treatment, largely for nutrient removal to help discourage regrowth on microorganisms in storage or in the delivery system. Common treatment techniques at the small to medium scale include rotating biological contactors, sequencing batch reactions, membrane bioreactors and constructed wetlands [174]. Biological treatment is generally followed by some filtration process and disinfection to ensure high quality water is produced [174]. Biological treatments are typically based on either aerobic processes or a combination of aerobic and anaerobic. In the aerobic stages, organics are reduced primarily to carbon dioxide and ammonia is converted to nitrates. Anaerobic stages can then be used to convert nitrates to nitrogen gas. Some biological phosphorus removal can also take place at this stage [181].

Rotating biological contactors (RBC) use a partially submerged support (on which microbes are grown) that slowly rotates in a tank through which the wastewater flows. The constant submersion and re-exposure to air allows keeps the system to maintain aerobic conditions in a smaller space and for lower power usage than other systems [181]. This makes it particularly attractive for small scale grey water treatment. The nature of RBCs means that while they remove organic contaminants they will also reduce the phosphorus concentration to some extent [182], meaning the nutrient value of the water is decreased. When combined with UV disinfection, RBCs have been shown to produce water of sufficient quality for toilet flushing in Germany [183]. In terms of cost an Israeli study has shown that RBCs can be economically viable at 1.9 $ML.yr^{-1}$ treatment rates [184].

Sequencing batch reactors (SBR) are, as the name suggests, a batch treatment technique. Water is collected and, once enough is present, it is transferred to the reactor tank where it undergoes biological treatment, is allowed to settle and the clean water is removed [181]. It is very similar to traditional activated sludge treatments used in sewage treatment, but has a smaller footprint and generally requires less capital investment [181]. The flexibility of SBR is of particular interest as it can easily be adapted to different treatment flows and changes in unit processes [181]. It is, however, more complicated in terms of control making it somewhat unattractive [181].

Membrane bioreactors (MBR) combined the traditional sewage treatment technologies of activated sludge treatment with membrane filtration [185]. This means that effective solids removal can be achieved coupled with biological treatment (removal of organics and some nutrients) in a small footprint [186]. MBRs are probably the most efficient systems with regards to removal efficiencies [174], however they require significant amounts of energy and have high capital and operating costs [186]. The same Israeli study investigating RBCs found that MBRs were only economically feasible when treatment rates exceeded 10 $ML.yr^{-1}$ [184].

Where space is available, wetlands treatment is generally considered a good option due to its low maintenance requirement and high visual amenity [98]. Constructed wetlands treatments for stormwater were discussed in Section 3.3.3, however in grey water treatment a different approach is generally required. Constructed wetlands can provide both physical and biological treatment via sedimentation in the first flooded zone, filtration through the macrophyte (shallow vegetated) zone and biological treatment, primarily in the macrophyte zone but also in the final storage lake [98]. Importantly, wetlands treatment relies heavily on the periodic flooding and drying of the macrophyte zone [98]. While the periodic flows of water generated by storm events are ideal in generating this for stormwater treatment, grey water flows are quite constant and consequently need a different approach. While stormwater treatment tends to use surface flow wetlands, for grey water and sewage treatment the use subsurface flow seems more common [187, 188]. By this it is meant that the water to be treated flows through the soil of the vegetated area rather than over the surface [181]. This gives additional benefits in that exposure to the potentially higher bacterial loads present in grey water is minimised [181]. Issues related to odour and mosquitoes are also minimized [181]. However, the costs of such systems can increase significantly [181] due to the need to import a soil with a percolation rate that is sufficient for treatment.

Disinfection is almost always required for grey water treatment. This is to achieve the final log reduction requirements as set out by the Australian Guidelines for Recycled Water [5]. Section 2.2.6.5 outlined the general disinfection techniques used in recycled water streams. For grey water UV technology seems to dominate in terms of use [183, 187, 189] probably because does not require significant chemical storage. UV irradiation is successful in removing microorganisms, however it does not prevent regrowth, which, due to it nutrient content, is commonly cited as potential for concern in grey water recycling [186]. Chlorination would be more effective in this respect as it leaves a long lasting residual. However it may suffer from interferences if the organic content is high [125]. One new product utilizes stabilised hydrogen peroxide as a disinfectant. On a small scale this may be more suitable for disinfection that chlorination [190].

With the exception of constructed wetlands, it is unusual to see one technology used on its own. Typically a treatment train is established utilizing selected units described above. Some treatment trains that are used include:

- Sand filtration followed by membrane filtration and disinfection [174].
- Screening followed by sedimentation and disinfection [191]
- Filtration followed by activated carbon treatment (to adsorb organics), sand filtration and disinfection [192]
- Rotating biological contactor followed by sand filtration and chlorine disinfection [182]

Ultimately the treatment train that is chosen is dependent on local conditions such as space, the flow rate needing to be treated, the desired product water quality and the level of maintenance and labour that can be dedicate to the plant.

3.4.4 Advantages

Grey water has a reasonable nutrient value, particularly phosphorus, that is valuable for irrigation purposes. The presence of surfactants can also be valuable as they traditionally help with soil wetting [193]. While treatment will remove some of these compounds there will be some residual that will be of value. Some of the nutrients that are removed will become available through sludges as biosolids for fertilization, depending on the treatment technique used. Fertilization with biosolids can easily provide the necessary micronutrients to suit a turf's needs [9].

While it is sometimes debated, it is generally believed that microbial contamination of grey water is not as significant as in sewage [174]. The average values used in the development of the Australian Guidelines for Recycled Water supports this view [5].

Water availability for grey water is generally more constant and reliable than rainwater or stormwater and storage volumes could potentially be reduced. This would bring significant cost benefits.

3.4.5 Disadvantages

While the sizing of tanks may bring some costs benefits, overall costs can be particularly unattractive. Decentralized systems that are of an appropriate size for sports ground irrigation are going to incur costs, not just in building the plant, but also doubling the infrastructure to convey source separated grey water. The added cost can quickly make a project unattractive when considered from a retrofit point of view.

Another disadvantage is the potential for high presence of salts, particularly sodium, from products used in the households or local facilities. This has the potential to become damaging to turf and soil if it is not monitored. Calcium additions may be required on soils where sodium content is high. Otherwise the high energy reverse osmosis could also reduce the high sodium content.

3.4.6 Conclusions

Grey water as a less contaminated water would seem attractive as a potential irrigation source. While nutrient levels are reasonable they are not excessive and only treatment for the reduction of microbes may be required. The main hurdle to grey water use at the moment is in terms of unit costs and space allocation. Where space if available, wetlands treatment would be suitable, however where minimal space is available small footprint biological treatment systems are generally quite expensive and need larger flow rates to justify them.

3.5 Recycled Water (Black Water)

3.5.1 Introduction

Black water is ultimately sewage. It includes all wastewater from within a house, commercial or industrial premises. It can vary significantly in terms of quality based around the characteristics of the catchment. Higher levels of contamination typically come from industrial sources, while ground water infiltration will lead to changes in salt concentrations. While there can be a seasonal variation in volumes, the more significant impact comes during wet weather when illegal storm water connections can significantly increase the flow of water. While this does little to the concentrations it does place stress on any treatment process that is put in place.

Recycled water can also be generated in a number of ways: via centralized treatment plants, decentralized treatment plants and sewer mining. In general the difference between these is the scale on which treatment is provided. Examples of centralized treatment include Western and Eastern Treatment Plants in Werribee and Carrum respectively. These plants can provide recycled water on a large scale often meaning they can be more economical, however they have less control over the catchment and therefore typically have high levels of industrial input leading to higher salt and metals contents. Table 3.5 shows typical recycled water qualities from both Eastern and Western Treatment Plants. Decentralized systems are smaller, typically encompassing a small town or suburb. The lower flows can make the economics of treatment less favourable, however there is greater control over the catchment and it is possible to minimize industrial inputs. Finally sewer mining is probably the smallest scale in terms of recycled water production, making water production quite expensive. It also has little control over the catchment as it is typically an afterthought in the development of a sewage system. It does have a very small physical footprint and can be installed almost anywhere there is a sewer main nearby. This is typically seen as its most important advantage.

The requirements for treatment generally depend on the biological removal and are defined in the Australian Guidelines for Recycled Water [5]. However, the current Victorian EPA guidelines are different and it is common for water authorities and professionals to refer to Classes of recycled water. The definitions of these Classes are shown in Table 3.6. Typically Class A water is used for irrigation of sports fields, however Class B and C may be used where significant steps are taken to reduce access to the field during irrigation. Readers are referred to the EPA documents for more information [194].

3.5.2 Quality Issues

Recycled water from raw sewage can be variable depending on the source of water. While residential sewage is generally consistent (keeping in mind the variability due to product usage described in Section 3.4.2), industrial sources can bring about significant variation. Table 3.7 shows the results of a study of sewage in Melbourne, specifically identifying residential sewage quality. The data for industrial sewage has been derived from this, however its reliability due to the significant variations that occur in industrial processes is somewhat questionable. For decentralized systems operating in a purely residential catchment the residential sewage quality is probably a good estimation.

Table 3.5 Typical recycled water qualities from Eastern and Western Treatment Plants in Melbourne

Parameter	ETP Median [195]	ETP Maximum [195]	WTP Median [196]
Alkalinity	155	190	-
Aluminium	0.26	0.9	< 0.05
Ammonia	12.6	18.6	-
Arsenic	0.002	0.006	0.002
Biological Oxygen Demand	0	5	< 2
Cadmium	-	-	< 0.0002
Calcium	18.5	23	36
Chloride	-	-	430
Chlorine	5	5.7	-
Chromium	-	-	< 0.006
Conductivity (uS.cm-1)	918	988	1900
E. coli (/100mL)			
Iron	0.32	0.79	0.085
Lead	-	-	< 0.001
Magnesium	9.4	11	26
Manganese	0.044	0.55	0.064
Mercury	-	-	< 0.0001
Nickel	-	-	0.017
Nitrate	6.2	8.9	-
pH	7.1	7.2	7.4
Potassium	21	24	32
Sodium	100	110	290
Sulphur	64	65	
Suspended Solids	1.5	14	5
Total Dissolved Solids	458	511	1200
Total Nitrogen	21	21	21
Total Phosphorus	8.1	28.7	-
True Colour (PtCo)	80	180	20
Turbidity (NTU)	0.2	3.5	-
Viruses (FRNA)	< 1	< 1	< 2.5
Zinc	0.054	0.18	0.017

Table 3.6 Victorian EPA guidelines for pathogen levels in recycled water. Adapted from [123, 197]

Classification	Requirements
A	< 10 E. coli per 100 mL Viruses: 7-log reduction from raw sewage[1] Protozoa: 6-log reduction from raw sewage[1] < 1 virus particle in 50 L[2] < 1 viable helminth egg in 1L[2] < 1 protozoa in 50 L[2]
B	< 100 cfu per 100 mL Helminth reduction for cattle grazing
C	< 1,000 cfu per 100 mL Helminth reduction for cattle grazing
D	< 10,000 cfu per 100 mL

[1]According to the Guidelines for Dual Pipe Water Recycling Schemes. This is more commonly used for the definition of Class A water in Melbourne

[2]According to the Guidelines for the Use of Reclaimed Water

Table 3.7 Typical sewage qualities from residential sewage, industrial sewage and a mixed stream. Adapted from [198].

Component	Residential Sewage	STP Influent (mixed catchment)	Industrial Sewage
Aluminium ($mg.L^{-1}$)	0.745	0.933	2.8
Ammonia ($mg.L^{-1}$)	36.2	39	60
Arsenic ($\mu g.L^{-1}$)	2.3	2.6	5
Barium ($mg.L^{-1}$)	0.038	0.167	2.378
Boron ($mg.L^{-1}$)	0.263	0.263	0.259
Calcium ($mg.L^{-1}$)	9.26	17.2	355
Chromium ($\mu g.L^{-1}$)	3.2	31	259
Cobalt ($\mu g.L^{-1}$)	1.28	1.75	6
Copper ($mg.L^{-1}$)	0.062	0.077	0.348
Iron ($mg.L^{-1}$)	0.728	1.23	7.998
Lead ($\mu g.L^{-1}$)	13	68	1159
Magnesium ($mg.L^{-1}$)	4.925	9.9	72.8
Manganese ($mg.L^{-1}$)	0.048	0.218	2
Nickel ($\mu g.L^{-1}$)	4.2	14.3	193
Oil and Grease ($mg.L^{-1}$)	22	59	351
Potassium ($mg.L^{-1}$)	16.78	22.45	70.13
Sodium ($mg.L^{-1}$)	87.28	137	567
Strontium ($mg.L^{-1}$)	0.05	0.0945	0.859
Tin ($\mu g.L^{-1}$)	4.69	6.7	23
Total Dissolved Solids ($mg.L^{-1}$)	375	550	2513
Total Nitrogen ($mg.L^{-1}$)	57	61	97
Total Organic Carbon ($mg.L^{-1}$)	173	271	1176
Total Phosphorus ($mg.L^{-1}$)	7.3	4.7	
Zinc ($mg.L^{-1}$)	0.169	0.346	2.478

3.5.2.1 Salinity/Sodium content

One major cause for concern when recycling water from sewage is the salinity or salt content. This is because traditional techniques have little impact on sodium concentration. Sewers with high industrial inputs could suffer from elevated sodium levels as a result of neutralization of industrial streams or typical processing waters. The elevation of sodium in this case is significantly more than either calcium or magnesium and it is possible for treated waters to have SARs in an unacceptable range for turf and soil health [16]. Where an estimate is required one rule of thumb to estimate salt concentrations in recycled water is to take the potable concentration and multiply by ten.

Ground water infiltration of sewers can also be significant, particularly in older or poorly maintained systems. The chemical changes brought about by ground water infiltration depend entirely on the local groundwater quality. While in most areas this will increase the calcium content more than the sodium, sea water intrusion into ground water due to over abstraction can lead to significant increases in the sodium content [199]. This is turn leads to unacceptably high SARs for irrigation and care must be taken.

Due to problems with sodium content, it is generally recommended that recycled water from municipal wastewater not be used for irrigation on clay soils and instead it should be used only for sandy loams to sand soils [16].

3.5.2.2 Boron

Another major source of concern in recycled water is boron and the potential for boron toxicity. In the past boron was used in a number of cleaning products [16]. However, this has decreased substantially over time and the most significant source of boron is now in faecal matter [169]. This is well below the recommended limits for boron and it should not be a problem in a residential catchment [16]. Still, it is often recommended to remove clippings from turfs irrigated with recycled water in order to minimise the potential for the accumulation of boron in the soil [16].

Industrial contamination from boron is a possibility from some processes. This would, however need to be assessed on a case by case basis.

3.5.2.3 Nutrients

Phosphorus and nitrogen are available in significant quantities in raw sewage due to their high content in human extreta. While treatment will reduce these concentrations, some content will remain. The use of recycled water for irrigation is considered beneficial as the nutrients are provided more regularly than by fertilization [16]. There are claims that using recycled water will provide all the phosphorus and potassium content a turf will need [16], however this can be variable depending on the turf and soils used.

While the presence of nutrients is generally positive, overapplication can be a concern. One particular concern is nitrogen that has been flagged as providing 2-3 times the requirements in some recycled water sources [200]. The form of phosphorus and nitrogen applied during irrigation tend to be soluble and not all are entrapped within the turf. It is possible to washout some of the applied nutrients. This is potentially damaging to local waterways and must be carefully regulated.

3.5.2.4 Alkalinity

The alkalinity of recycled water can be quite high. The impact of this on turf comes through changes in the soil pH and ultimately the microbial populations there [16]. The microbes are important to the conversion of nitrogen compounds to more suitable products for plant uptake. Alkalinity in the form of carbonates can also lead to deposits forming on the leaves of turfgrass. High alkalinity therefore is undesirable. The bicarbonate concentrations should be maintained below 90 $mg.L^{-1}$ and definitely below 500 $mg.L^{-1}$ [16]. Where this is not possible it addition of an acidic compound may be required.

3.5.2.5 Metals

In terms of metals, only two of the raw sewage concentrations in a mixed catchment trigger the trigger the long-term irrigation values specified by the Marine and Fresh Water Quality Guidelines [106] and may need to be monitored. These are iron and manganese. In general treatment process will reduce these somewhat. Manganese levels only just reach the trigger value and are unlikely to be a significant concern. Iron on the other hand could be significant, although it has been noted previously that small concentrations of iron in irrigation water may be beneficial to a turf [9].

3.5.2.6 Free Chlorine

Free chlorine in recycled water could be a significant concern as it can be used in high concentrations as part of the disinfection process. It is possible for the free chlorine content in recycled water to exceed what is seen in potable water. Chlorine levels should be maintained below 1 $mg.L^{-1}$ although up to 5 $mg.L^{-1}$ may only be moderately damaging [16]. Chlorine can be reduced if required by the addition of sodium metabisulphite. Where possible, disinfection using other techniques such as ozonation or chloramination may be more appropriate.

3.5.2.7 Biology

Common pathogenic species found in raw sewage and recycled water were described in Table 2.23 in Section 2.2.6.3. These are the focus of the Australian Guidelines for Water Recycling and their removal is discussed in detail in Section 2.2.6.

3.5.3 Treatment

3.5.3.1 Pre-treatment

Pre-treatment involves simple techniques designed to remove large insoluble objects from sewage. The two most commonly used processes are screening and grit removal. Screening focuses on removing items such as paper, sanitary products and litter that find their way into the sewers. Grit removal focuses on settling out the larger particles from sewage. Both processes generate solid waste streams that must be disposed of while also removing a portion of the incoming water.

3.5.3.2 Primary Treatment

Primary treatment focuses on physical processes for removal of contaminants from sewage. Though it is considered a physical process it often employs the use of chemicals such as ferric chloride or alum to aid in flocculation and coagulation processes. The ultimate focus is to remove smaller particles by forcing them to combine into larger particles and allowing them to settle to the bottom of the trough or tank. This is generally combined with a small amount of grease or oil removal that can form a scum at the surface of the water. In some parts of Australia this is the minimum amount of treatment required for discharge of water to deep ocean outfall. It is not sufficient, however, for creating irrigation water from sewage.

3.5.3.3 Secondary Treatment

Secondary treatments tend to revolve around biological processes for the reduction of organic and nutrient contents is water. On a large scale these may include lagoon treatments, activated sludge treatments or membrane bioreactors. These processes typically use aerobic conditions to help convert ammonia to nitrates and organic compounds to carbon dioxide. The processes are quite energy intensive due to the need to pump air or pure oxygen into the water on a continuous basis [201]. Activated sludge treatments may account for 70 % of a tertiary treatment plant's electricity requirements [201]. The process generates also tends to generate a large amount of other wastes both solid and gaseous that will need to be considered. Solid sludges produced at this point are generally high in nutrient content (removed from the wastewater stream) and after treatment to remove microbial contaminants and to dry them out may be used as a fertilizer. Gaseous products include carbon dioxide, nitrous oxide and methane, all of which are greenhouse gases. The worst of these is nitrous oxide [167]. It can be formed during the conversion of ammonia to nitrogen dioxide although the percentage is fairly small.

While conventional techniques typically stop here, some processes will aim at further nutrient reduction by adding an anaerobic stage. In this stage nitrates are reduced to nitrogen gas and phosphorus may also be more effectively removed. This significantly reduces the amount of nutrients available in the irrigation water which may be beneficial where high nutrient content runoff and fouling of irrigation pipes are a concern. The drawback is a significant increase in the production of greenhouse gases, particularly nitrous oxide and methane.

3.5.3.4 Tertiary Treatment

Tertiary treatment typically refers to disinfection processes. Typically this involves chlorination, but may also include ozonation or UV irradiation. Disinfection is an oxidative process and also brings about a small reduction in the remaining organics. The Where chlorination is used, care must be taken to ensure the residual is not too high for irrigation (preferably less than 1 $mg.L^{-1}$ [16]). While the other techniques may be less toxic overall to plant life the main reason for this is their shorter half life and the fact there is less or a short lived residual [125]. This in turn may lead to regrowth problems where the water is stored for long periods.

3.5.3.5 Higher Treatment

Where salt and particularly sodium concentrations are elevated, higher treatments may be required. These typically revolve around the membrane filtration technique reverse osmosis. This technique, also used in seawater and brackish water desalination, effectively removes most components from contaminated water streams. In recycled water it is typically used to provide high quality water for drinking or sensitive industrial processes such as steam generation and electronics manufacture [202]. This generally means the water is over treated, however if the salt content is too high, the water cannot be used otherwise.

Reverse osmosis processes can be very energy intensive when compared to other sewage treatment processes (approximately 1.7 kWh per kL of produced water for a brackish water process [203]). This significantly increases the production costs of water. Also the membranes used are not tolerant of chlorine [204]. As a result it is generally more economical to use secondary treated wastewater as a feed to higher treatment processes than tertiary treated [202]. This water can also contain some suspended solids that will foul and reduce the performance of RO membranes. To prevent this microfiltration may be employed. This further increases energy consumption [205].

While the benefit of using advanced treatment is to remove unwanted salts, the process will also remove nutrients and results in the formation of a concentrated stream of water that must be disposed of. Though it is highly variable, a quick estimate of the water losses would suggest that for every kL of water produced 250 to 670 L is lost (derived from [206, 207]). The nutrient content will be reduced to at most 10% of concentrations prior to RO [208]. While the nitrogen component may be lost, there is a possibility of recovering phosphates separately, either by precipitation from the concentrate stream or through the use of another membrane prior to RO. These technologies are still being explored and commercialisation may not occur until sometime in the future.

3.5.4 Inherent Advantages

Sewage is a rich source of nutrients, both nitrogen-based and phosphorus-based. While some treatment techniques can significantly reduce this, the benefit of local of decentralized production is the availability of biosolids. If the catchment has been properly managed and contains almost exclusively residential dwellings then biosolids can be easily used as an inexpensive fertilizer for the sports field. Importantly trace nutrients are also present in biosolids and this should ensure micronutrient deficiencies do not occur [8].

In general, not all nutrients are removed during the treatment process, however. The remaining nutrients will be delivered to the turf during irrigation. This will significantly reduce the requirements for fertilizer use onsite. Research has estimated that phosphorus application rates would be roughly equal to demand while nitrogen requirements could easily exceed requirements in terms of fertilization [200]. According to this study the average Canberra resident would contribute the equivalent of 50 kg of Multigro fertilizer for one year and 100 kg of nitrogen. This compares to a recommended application of 40 kg each year for 500 m^2 of sports field.

For Melbourne, to estimate the mass of nutrient delivered in $g.m^{-2}.yr^{-1}$ the following equation may be used:

$$m_{y_{delivered}} = \frac{V_{irr}}{A_{field}} \times c_y$$

Where V_{irr} is the annual irrigation delivered in $L.yr^{-1}$, A_{field} is the area of the field is m^2 and c_y is the concentration of species y in $g.L^{-1}$. If we were to assume an average sized field (1.7 ha or 17000 m^2) with a water requirement of 3.5 $ML.yr^{-1}$ (3500000 $L.yr^{-1}$) using irrigation water from Eastern Treatment Plant (c_N=0.021$g.L^{-1}$ [195]), then 4.3 $g.m^{-2}.yr^{-1}$ of nitrogen should be delivered to the turf through irrigation. Assuming a couch turf this would provide the equivalent for one growing month. Increasing irrigation would increase the nitrogen delivered and therefore the demand that may be met by irrigation is highly dependent on the irrigation volume used for a field.

The availability of recycled water is another significant advantage. It is available at a relatively constant rate, although there are slight seasonal variations. This makes any treatment that may be needed easier to manage. The other possibility is that already treated recycled water could be made available by the local water authority. This is similar to a potable water system in that the water is generally available on demand, giving a greater water security than weather-dependent sources such as roof water.

3.5.5 Potential Disadvantages

While recycled water is somewhat independent of climate and may be regarded as drought tolerant, it is questionable whether it can be referred to as drought-proof. During water restrictions, changes in consumer behaviour, both commercial/industrial users and residential users, result in decreases inflows to sewage treatment plants, and ultimately limit the amount of recycled water that can be produced. In some part of the United States, over allocation of recycled water resources has meant that during times of drought, even these water sources are often placed under restricted use. The possibility of recycled water being restricted should be considered when developing a water management plan.

While recycled water can be a useful source of nutrients, sometimes the nutrients are available in concentrations that are too high either for the irrigation system or the soil. Irrigation with recycled water has led to higher nitrogen and phosphorus in runoff [209]. Concurrently, the availability of phosphates in particular can lead to increased microbial growth and ultimately biological fouling [5]. Nutrient removal or reduction is a possibility during treatment processes, particularly through more advanced biological techniques or reverse osmosis. It is possible to reduce the nutrient content sufficiently, while maintaining some of the benefits of its presence.

Some of the controls placed on the use of recycled water can make its use restrictive. Limiting irrigation times or practices may not be suitable to some sites or may increase the financial burden of its use. At these sites recycled water may not suitable.

Salinity issues can also be significant in recycled water. Where the SAR is high, periodic liming of the soil may be required, or addition of calcium salts to the irrigation water. This is particularly important for clay rich soils as these are impacted more significantly be saline waters [16]. Recommendations suggest recycled water only be used on soils that have a texture of or sandy loam or coarser [16].

The final disadvantage is applicable specifically to sewer mining – access rights. Negotiations over access to water from sewers cannot be considered a straightforward process. Different water authorities are responsible for different sections of sewers within Melbourne and extraction from some points will not necessarily be supported due to potential impacts of sewers downstream of this point. These issues and the time associated with overcoming them must be considered as part of the scoping of potential projects.

3.5.6 Conclusions

The high nutrient content of recycled water is a significant benefit to irrigation. Some authors have claimed that this will meet all of a turf's potassium and phosphorus requirements and almost all of the nitrogen. At a minimum it should significantly reduce fertilizer requirements. Where a decentralized treatment system or sewer mining is employed the generation of sludge/biosolids will have the additional advantage of providing a mincronutrient rich fertilizer.

While salinity may be an issue with recycled water in some areas this can be mitigated somewhat by further treatment, although this will come at increased expense. Where salinity is high but not extreme the use of recycled water should be limited to sandy loam soils and coarser, it should not be used on clay-based turfs.

3.6 Ground Water

3.6.1 Introduction

Ground water is included in this discussion as alternative water source. This does not mean it is naturally sustainable. Sustainable use of ground water is difficult to ensure, but essentially requires that water enter the aquifer at a rate equal to or greater than that which it is abstracted. This may be achieved through aquifer storage (where a treated wastewater is pumped into or percolated into the water table and later extracted for use), or through aquifers that have a naturally fast recharge rate (however this means they are dependent on rainfall and therefore not drought-proof). Ground water sources can also vary significantly in terms of quality. Throughout the Melbourne region ground water is very rarely used due to a lack of surface aquifers and due to increasingly poor water qualities in those that are present. Sea water intrusion is also a significant concern, particularly in the Altona region.

3.6.2 Quality Issues

Table 3.8 Typical water qualities from bores in the lower Dandenong Ranges. Adapted from [210]

Parameters	Low elevation basalt bore	Low elevation sedimentary bore
pH	7.3	6.7
TDS ($mg.L^{-1}$)	435	537
Dissolved O_2 ($mg.L^{-1}$)	8	<1
Ca ($mg.L^{-1}$)	37	26.8
Mg ($mg.L^{-1}$)	32	37.4
Na ($mg.L^{-1}$)	56	54.5
K ($mg.L^{-1}$)	4	1.8
Si ($mg.L^{-1}$)	18.6	25.6
SO4 ($mg.L^{-1}$)	6	< 0.1
Cl ($mg.L^{-1}$)	103.9	118
Br ($mg.L^{-1}$)	0.28	0.36
HCO_3 ($mg.L^{-1}$)	177	230

The main chemical constituents of ground water are dissolved minerals, typically calcium or magnesium based. Table 3.8 gives list some typical groundwater qualities from the foothills of the Dandenong Ranges. High calcium content leads to a hard water, meaning it is difficult to make a soap foam, but is preferential for irrigation over a sodium rich water. In general the increased residence time of ground water (that the longer it takes to flow, and ultimately, the lower in elevation it is taken from) the higher the TDS content [210].

The local geology will have an impact on water quality in two ways. As noted earlier the dissolution on minerals typically occurs in aquifers and as ground water drains. A study in the Dandenong Ranges has looked at the two most common geological systems in the Melbourne area tertiary basalt and Silurian-Devonian sedimentary rock [210]. The first dominates in the west of Melbourne while the second dominates in the east. While basalt based groundwater has a reasonable TDS, that of the sedimentary aquifers tend to be higher where residence times are longer. Importantly the ratio of sodium to calcium in the sedimentary aquifers tends to higher. Also of importance is the fact that basalt groundwaters show signs of continuous infiltration of surface waters which would make them more susceptible to contamination from practices occurring here.

Another important point to consider is the dissolved oxygen content. Ground water aquifers are generally anoxic (i.e. free of oxygen) [100]. This controls the chemistry and biology of the water within the aquifer. Under such conditions most species exist in their reduced forms. That is to say that nitrates can be transformed to ammonia, sulphates to more acidic sulphides and metals to their reduced state such as iron(III) salts to the more soluble iron(II). One problem seen with ground water is the slow oxidation of these reduced species that occur once the water is exposed to the atmosphere. This is one of the reasons that aeration of ground water is typically practiced prior to its use [211].

The presence of dissolved metals can be a concern in this respect. Iron can be, and generally is, present in high concentrations and some heavy metals such as arsenic and selenium can also be an issue. While iron can be toxic to turf, its presence at low levels can be beneficial [9]. However its presence in a reduced form that is then oxidised to the less soluble iron(III) leads to precipitation in storage media or in pipes. This may not be an issue where a sufficient residence time in a tank is used, but could lead to damage to pumps and sprinklers if not properly treated. Aeration and oxidation of the water followed by filtration or detention should reduce this impact.

Arsenic is present in a number of minerals around Australia and Victoria [212] and can lead to leaching of arsenic into groundwater. There is a theory that as abstraction occurs this is accelerated due to the oxidation and release of mineral arsenic in the aquifer when water is replaced by air and subsequently rewetted [213]. In some areas this has lead to problems with ground water use as a drinking water due to excessive arsenic levels [214]. The concentrations may also be excessive for irrigation. Treatment may be required to remove this species.

The other major point of concern in groundwater is contamination from infiltration of chemicals from the sources. This contamination can come from point sources or non-point sources. Examples of point sources include industrial sites [211, 215] and petrol stations [216, 217]. These generally come from spills and leakages and can increase the levels of unwanted heavy metals or organics. Petrol stations and the associated underground storage tanks, in particular can contribute to increased refined petroleum levels in ground water, leading to high levels of toxic benzene, toluene, ethylbenzene and xylene [217]. In the United States this has led to these compound being the most frequently detected compounds in drinking water supplied that rely on ground water [217]. Where these facilities may be present in the charging zone for an aquifer, particularly near the bore to be used, treatment or avoidance should be considered.

Non-point sources are more complicated. The most significant however is the infiltration of nitrogen and phosphorus from fertilizer use in agriculture, gardens and open space management [218]. This can be significant particularly where there is high rainfall [219]. Similar sources can also introduce pesticides and herbicides to groundwater [220] that if significant enough will require some treatment to remove.

3.6.3 Treatment

As a minimum for groundwater aeration is often performed. This helps to remove unwanted volatile compounds such as VOCs (including petroleum components) [217], carbon dioxide [221] and hydrogen sulphide [222]. The process of aeration can also assist in the oxidation of components such as iron and manganese, though this is achieved more efficiently if an oxygen enriched stream is used [221]. The oxidation of these species, coupled with the pH increase of carbon dioxide removal helps facilitate precipitation. Subsequent filtration using sand filtration or microfiltration can then be used to remove the precipitate [221].

Where salt contents are high, demineralization may be required. This can take the form of either reverse osmosis or ion exchange. Reverse osmosis is effective at removing almost all salts from solution. The main problem that could arise is with scaling of the membrane which will increase operating costs as well as disposal of the concentrated waste stream. While reverse osmosis is probably the most efficient technique for removing sodium and chloride salts, scale formation from calcium-based salts is common. Calcium carbonate or phosphate concentrations will generally limit the recovery of water is such circumstances. While research is ongoing in improving recovery where these compounds dominate [223], nothing has reached a commercially viable state at this time. Consequently either low recoveries, or increased operating costs must be expected.

The concentrated waste stream produced via reverse osmosis must also be disposed of. While discharge to sewer may be an option, there are generally restrictions on salt concentrations of streams discharge to here. This can make disposal costly in the long run and ultimately make reverse osmosis of groundwater unattractive.

Ion exchange operates on the basis of adsorbing specific ions selectively from a water stream. There is a limit to the amount of adsorption that can occur however, and periodic regeneration of the ion exchange material is required. This will result in increased operating costs due to chemical requirement and disposal [224], however it can be more efficient where a specific component (e.g. arsenic) is targeted for removal rather than all components in the water.

3.6.4 Advantages

Ground water can provide a relatively clean and high calcium-containing water that is suitable for irrigation, but qualities vary significantly.

Where no or minimal treatment is required, storage is generally not an issue for groundwater as the aquifer will act as a storage device. Recharging the aquifer with treated waters is also an option. This would potentially reduce the cost, and more importantly reduce the footprint, of storage of alternative water sources.

3.6.5 Disadvantages

Ground water is not necessarily sustainable. Care must be taken to ensure that the rate of extraction does not exceed the rate of recharge. One step in doing this can be to use the bore as a storage area for other alternative waters, such as storm water, that may become available when they are needed least creating a long-term storage requirement. Natural recharge is also climate dependent. The impacts of climate change are generally expected to reduce recharge rates of ground water [225] and thereby making extraction a less sustainable option. In some parts of Australia, historical over-abstraction of ground water means this source should probably be avoided.

Ground water is also not available everywhere. It is highly dependent on the local geology. Some aquifers are too deep to easily reach and this is the case in many parts of Melbourne. Deeper aquifers also require more energy to extract from, making them less sustainable overall.

Over abstraction of ground water can also lead to a decline in water quality over time. This could mean significant changes in some components that ultimately make the water unusable without further treatment. This is believed to be a particular problem with arsenic where increased abstraction leads to oxygen entering the aquifer and forming more soluble arsenic salts that can make their way into the groundwater that is subsequently abstracted [213]. These types of changes should be avoided by minimising abstraction and ensuring that abstraction rates do not exceed recharge.

3.6.6 Conclusions

While ground water can represent a clean and useful irrigation water, it must be carefully managed to ensure sustainable use. Where natural recharge rates are lower than water requirements, ground water abstraction should either cease or artificial recharge should be initiated.

Ground water quality is generally sufficient for irrigation without much treatment, however it is very location dependent and contamination of ground water from human activities can impact on the ability to safely use groundwater.

3.7 Desalinated Water (Brackish Water and Sea Water)

3.7.1 Introduction

Sea water and brackish water both have high salt contents that are generally unsuitable for irrigation without treatment. Sea water is sourced either as a surface water from a bay of coastal area or from "beach wells", i.e. sea water sourced from below the surface [226]. The composition varies somewhat from site to site but Table 3.9 shows a standard breakdown of sea water. Brackish water is less salty and is defined as water with a total dissolved solid content of between 1000 and 10000 $mg.L^{-1}$ [222]. It is generally sourced from ground water, waste water and tidal mixes of salt and fresh water that occur in estuarine rivers. This section will only consider the last of these with ground water and wastewater discussed in Sections 3.6 and 3.5 respectively.

3.7.2 Treatment

In order for either brackish water or sea water to be suitable for irrigation some form of desalination is required. On small scales this is typically performed using reverse osmosis [180], although some thermal and charge based separations are also becoming popular.

Table 3.9 Typical composition of seawater. Adapted from [227]

Parameter	Concentration
Sodium ($mg.L^{-1}$)	10733
Chloride ($mg.L^{-1}$)	19344
Magnesium ($mg.L^{-1}$)	1294
Sulphate ($mg.L^{-1}$)	2712
Calcium ($mg.L^{-1}$)	412
Potassium ($mg.L^{-1}$)	399
Hydrogen carbonate ($mg.L^{-1}$)	142
Boron ($mg.L^{-1}$)	4.5
Total Nitrogen ($mg.L^{-1}$)	0.4
Total Phosphorus ($mg.L^{-1}$)	0.07
Copper ($mg.L^{-1}$)	0.0002
Iron ($mg.L^{-1}$)	0.00006
Zinc ($mg.L^{-1}$)	0.0004
Manganese ($mg.L^{-1}$)	0.00003

3.7.2.1 Reverse Osmosis

Osmosis is the process of water moving through a membrane from a more dilute solution to a concentrated solution. In reverse osmosis (RO), the process is reversed by applying a high pressure to the concentrated side and forcing water through the membrane to the dilute side. The pores (or holes) in the RO membrane are small enough to prevent that while water may pass through, the passage of salts is prevented resulting in a quite pure water. Typical rejections, or removal efficiencies, for sea water RO are around 98-99.5% [228, 229] and around 90-95% for brackish water [207]. The reason for the difference lies in differences in the membrane and the need to optimize the rate at which water passes through the membrane. There is also a difference between the rejection of different ions and species, with ions like calcium, magnesium and sulphate having higher rejections than sodium, potassium and chloride [207]. This can influence the quality of the final water, depending on how the water was treated.

The amount of water recovered from RO processes depends on the quality of the water being treated. For sea water this is limited to about 50 % [229] while brackish water can range from 60 to 80 % [206, 207]. To achieve this recovery high pressures are often required. For sea water desalination a pressure of at least 50 bar is required and often operating pressures are higher [230]. Brackish water on the other hand needs a slightly lower pressure (often 20 to 30 bar). The high pressures and low recoveries have a large impact on energy requirements. Typical energy requirements are of the order of 4.5 kWh/kL of water produced for sea water and 1.7 kWh/kL of water produced for brackish water production [203]. This energy requirement is significantly higher than other water or wastewater treatment technologies and coupled with something like microfiltration adds to the ongoing costs of seawater desalination. On the small scale typically required for sports field or open space irrigation, the ongoing costs will easily be greater than the cost of potable water. The energy requirements also contribute to the large carbon footprint of the technology. This can be reduced by coupling reverse osmosis with renewable energy sources such as photovoltaics [231, 232], wind turbines [231] or wave power [231]. These have previously been proven on a small scale for brackish water treatment in remote communities [233, 234].

Sea water RO can be operated in two modes, single pass or double pass. The two are similar in terms of recovery [226] however the water qualities vary significantly [228]. Single pass refers to the fact the water is treated once, while in double pass the product water (or permeate) from one RO is fed to a second RO unit to further reduce salt concentrations. Quality variations are significant with single pass RO generating water with a total dissolved solids content of 350 to 500 $mg.L^{-1}$ [226, 228, 235, 236], while a double pass system may produce a TDS as low as 2 to 11 $mg.L^{-1}$ [228]. Other difficult to remove components such as boron can also be more effectively reduced using a second pass [228].

Another significant cost associated with reverse osmosis treatments is the disposal of the waste stream. For low recovery sea water systems this may not be too significant as the reject stream may not be too much more concentrated than seawater and disposal back to the ocean or bay could be possible, assuming the necessary permits are granted. For brackish water desalination the concentration increase is significantly greater making disposal more complicated. While it may be possible to dispose of the water in the sewer this would be dependent on the requirements of the local water authority. Otherwise reject water would need specialist disposal.

3.7.2.2 Thermal processes

Thermal processes are typically more energy intensive than reverse osmosis, but can produce a water with lower salt content. There are two main techniques that are utilized for small scale desalination:

- Solar distillation – For small scale water desalination solar stills are often recommended [180]. They operate by focusing sunlight on a pool of water leading evaporation. The water vapours condense on the glass surrounding the still and are collected. Aside from solar energy there are no significant energy requirements making it particularly attractive. Having said this, its efficiency is very low. It takes one day to produce 4 L from a 1 m^2 plot [180]. On the scale required for sports field irrigation, the size of a solar still would probably make it unsuitable.
- Membrane distillation – While it was developed some decades ago, recent advances in membrane technology have brought membrane distillation closer to commercialization. The temperatures that can be used for membrane distillation are generally lower than for other thermal processes reducing somewhat the energy requirement. However, it is still more energy intensive than reverse osmosis. This can be offset though by tying the technique with solar heating of the water [231]. This has been successfully demonstrated in the past on both large and small scales [231]. Geothermal treatment has also been effectively used on a small scale [232]. The water produced by membrane distillation is also of higher quality than what is seen by reverse osmosis [231, 232]. The most significant drawback is the fact it is not yet commercialised making adoption of the technology difficult, expensive and not without some risk.

3.7.2.3 Charge-based separations

One of the more typical charge-based separations is electrodialysis (ED). The technique uses an electric field to separate ions and force them through selective membranes to remove them from the water. To prevent precipitation the direction of the electric field may be reversed every twenty minutes [231]. ED has been used for brackish water treatment for some time and can be considered a mature technology [231].

The energy requirements of ED come from the applied electric field and the pumping energy. It is typically seen as having a higher energy requirement than reverse osmosis [231], with brackish water treatment typically needing 3 kWh/kL [205]. Integrating with photovoltaics has occurred previously with success, though it is limited to brackish water desalination [231].

3.7.3 Quality Issues

The quality of desalinated water is a function of the water used and the treatment processes employed. As the main commercial technique for desalination the following discussion applies primarily to water produced by reverse osmosis.

3.7.3.1 Issues related to the water source

Sea water around Port Philip Bay is particularly impacted by temperature fluctuation. Temperatures from winter to summer can vary from 9 to 25 °C [237]. While salinity fluctuations also occur (from 33 to 35 $g.L^{-1}$ [237]) temperature fluctuations could be more difficult to cope with due to strong variation in rejections and ultimately the composition of product water. Every 1 °C increase in temperature brings about a 3-5% increase in permeability of ions and water [238]. This can translate to 0.1 to 0.2 $mS.cm^{-1}$ in conductivity for a 5 °C change in inlet temperature where flux is maintained at constant levels [236]. Alternatively, where it is not controlled flux can vary significantly.

Variations in water quality can place significant demands on the treatment process and result in fluctuations in the product water quality. Water sourced from areas where fresh and salt water mix can be significantly influenced by tidal variations. High tides will result in higher salinity for the sources water while low tide will give the opposite. This can interfere with the running of the plant.

3.7.3.2 Issues related to the treatment

Boron rejections in reverse osmosis are very low ranging from 30 to 90 % for a single RO pass under a neutral pH [228]. This can result in a boron content of 1 to 2.5 $mg.L^{-1}$ in product water from sea water [228]. This has raised concerns for irrigation and many large scale desalination projects that provide water to irrigators as well as for drinking uses multiple passes specifically to deal with this issue [228]. It is also possible to polish RO treated seawater with ion exchange or adsorption based technologies.

Single pass RO treatment, while reducing salt content, can still leave a significant quantity of salt in the permeate. Typical value quoted for total dissolved solids concentrations after one RO pass range from 300 to 500 $mg.L^{-1}$ [226, 228, 235, 238, 239]. Keeping in mind that calcium and magnesium are more easily rejected than sodium [230] and the concentration of sodium is significantly higher than calcium and magnesium in seawater (See Table 3.9), this could be detrimental to clay or loam based soils. However, keeping in mind that sea water can only be sourced from coastal areas and these soils are typically sandy, this may be less of an issue.

The age of the system will also impact on the quality of RO permeate. Degradation of membranes over time leads to a loss in rejection. This has been quantified as being 10% increase in permeability for each year of operation [238]. The use of RO systems for desalination needs to keep this property in mind when aiming for a specific water quality.

3.7.4 Inherent Advantages

Sea water desalination, if designed correctly, is the only water source that is truly drought proof. The oceans represent a vast and constant supply of water that, with the proper treatment, can be made suitable for irrigation.

While treatment processes are very energy intensive, they have been shown to integrate well with renewable energy and research in this field is quite strong.

3.7.5 Disadvantages

Energy requirements for desalination can be high especially when compared to other water treatment techniques. This impacts particularly on the ongoing costs of water treatment. While there have been numerous successes in integrating renewable energy this comes with increased capital costs.

The high energy requirement also leads to poor public perception when compared to other water sources, although opinion is still generally favourable. Integration with renewable energies should help with these issues.

Where the water is not properly treated boron and salinity may be an issue for irrigators. Where this is the case coarse low clay soils should be used and clipping should always be removed after mowing. Using these two management strategies should help to reduce the impacts of poorer quality water.

The formation of a concentrated waste stream can complicate sea water treatment due to disposal concerns. Discharge to sewers is not likely to be an option due to the high salinity of the waste stream. Location near the sea or bay may help with disposal, particular where low recovery systems are used as these wastewaters are only slightly more concentrated than the seawater they were drawn from. Licensing would however be required for the discharge.

3.7.6 Conclusions

In combination with renewable energy and careful waste management, desalination of saline water would be considered one of the more sustainable water sources. It is the only water supply considered here that is truly drought proof. While some treatment techniques may produce water that is high in boron or salt content, this is generally manageable.

Chapter 4 - Conclusions

A range of sustainable options for sports fields have been presented. These range from changes to turf types to changing the irrigation water.

A change from cool-season turfs to warm-season or artificial turfs will help to reduce water demand. Concerns that typically arise about changes in gameplay, injury rates and appearances are not necessarily too significant. Gameplay characteristics such as ball bounce and ball roll will change with changes in turf surface. However turf surfaces seem to generally remain within the requirements specified by the sport's regulatory bodies. Differences in gameplay will only come about through perceptions of surfaces, as has been witnessed in soccer on artificial turfs. In this case however it was found the sportsmen adapted to the changed conditions, limiting the impact. Injury rates between the three turf types are generally similar, although there is an increase in the incidence of minor injuries such as abrasions and turf burn on artificial turfs. The major consideration with turf appearance is with winter dormancy of warm-season turfs. This can lead to significant discoloration. There are solutions however with hybrid couch grasses such as Wintergreen having been specifically bred to retain their colour of winter. Overseeding with cool-season grasses during winter will reduce the water requirements over summer months, while maintaining the more traditional cover over winter.

Changes in irrigation delivery can be brought about by utilising subsurface techniques, such as subsurface drip or subirrigation, instead of sprinkler or spray. Of these subirrigation appears to be the least water intensive with 50-90% reductions in water use compared to sprinklers. Subsurface drip irrigation is more complicated in that it does not always bring a reduction in water usage, however the quality of the turf and maintenance requirements were seen to reduce.

Six alternative water sources were considered:

- Rain water
- Storm water
- Grey water
- Black water
- Ground water
- Desalinated water

Of the six, desalinated water is the only true drought proof water source, while grey water and black water recycling can be drought tolerant. The small volume generally collected as rain water typically means it is useful as a supplement but not as a sole source of water. Ground water recharge rates can also be slow making its use unsustainable, aquifer recharge using another water source can help to alleviate storage concerns while ensuring sustainable groundwater use.

Water qualities vary significantly, but the main concerns comes from salinity, metals and boron concentrations in the wastewater streams. Salinity is a concern for recycled black water, grey water, some ground water and desalinated sea water. It is of particular concern to the stability of the soil, particularly clays. Where salinity is high calcium addition is recommended and irrigation should be limited to sandy loam soils and coarser. Continual monitoring of the soil would also be required to ensure its ongoing structural stability.

Metals of concern in most alternative water sources revolve around copper and zinc. These corrosion product are of particular concern in some rain water and storm water sources as they are available at concentration that can be toxic to turf. Catchment management to reduce the presence of copper and galvanised metal surfaces and pipes should reduce the risk of contamination from these sources. Where this is not possible, ongoing soil monitoring should be practices.

Boron toxicity is the final component of concern, and though it has been identified in the past as a potential problem to recycled water cultural practices and product reformulation have limited this. Boron is really only of concern in desalination from sea water, due to the poor removal efficiency of boron in traditional technologies. Small scale systems may not be able to effectively remove boron and leave the turf exposed to toxicity issues. Removal of turf clipping after mowing should reduce this, but care should be taken when using desalinated seawater as a source of irrigation water.

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