THE ROLE OF CRACK WILLOW IN THE WETLAND WATER BALANCE, MOUTERE REGION, NEW ZEALAND

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ABSTRACT

The Waiwhero wetland (16 ha) is one of the largest wetlands in the Rosedale Hills, 35 km north-west of Nelson, New Zealand. It has an extensive cover of Salix fragilis L. (crack willow) and has been hypothesised to be a source of groundwater recharge for the Moutere aquifers, an important local groundwater system. However the wetland could also be a groundwater discharge zone, because of the geological boundary that it straddles. The overall aim of this study was to determine the direction of groundwater flux of the wetland by measuring the water balance, with particular emphasis on the transpiration rates from the crack willow trees.

The average daily transpiration (measurement was for 230 days) of crack willows in the wetland (6.4 mm/day) was close to twice the potential evapotranspiration (PET) for grassland (3.9 mm/day). The highest measured willow transpiration rate was 12.4 mm/day and the lowest was 0.8 mm/day. High transpiration from crack willows was due to the horizontal energy fluxes (advective energy), tree physiological characters and high soil water content.

The study established that the wetland is a groundwater discharge zone with, on average for the two summer periods (2008 and 2009), the net groundwater discharge being 4.8 mm/day. The daily water balance results between two major rainfall events showed that the initial discharge source was from the surrounding hills and later stabilized at around 6 to 14 mm/day. It was believed to be a contribution from the shallow and deep aquifers or a combination of local region inflow and aquifers.

The water balance showed that the main loss of water through the hydrological system of the wetland during summer was from the high transpiration of willows (7.7 mm/day). The extent of water savings estimated for the 16 ha wetland through a hypothetical situation of willow removal, and the assumption that it is filled with open water without any canopy cover, was 688 m³/day. However this water savings rate if applied to a large area of crack willow stands would be quite high. On similar lines it is important to understand the transpiration rates of other wetland tree species in New Zealand. This information would help in preparing regional council plans for the introduction of tree species in the wetland for better management of the water resources and sustainable ecosystem management.
CHAPTER 1

1. INTRODUCTION

In the Moutere region southwest of Nelson, there is a significant amount of groundwater abstraction in summer for agricultural\(^1\) purposes. Groundwater abstraction has increased rapidly from the mid 1980s, after deep wells revealed large quantities of water available from aquifers up to 500m deep (Davie et al., 2003). This led to the water resources in the Moutere aquifers being deemed fully allocated for the summer period (TDC, 2000) and no further water consents from those aquifers could be approved.

In 2001 and 2002 the Tasman District Council began an exploration project and drilled new bores in areas of the Moutere Valley to find out more about the hydrogeology, yields and recharge dynamics of the deep aquifers. The drilling and pump testing investigations in combination with isotopic (age) and chemical analysis of deep groundwater showed some limited deep groundwater that could be allocated but the quest to find large quantities was not successful (Thomas, 2006; TDC, 2006). This exploration helped the water users to an extent but in the long run it was important to understand more about the resources available and their sustainable limits. Presently the farming community in the Moutere is looking at groundwater as a potential resource for intensification of agriculture and potentially for community water supplies. In this regard any new insights into the ground water recharge mechanisms for Moutere aquifers would help the Tasman District Council in its decision-making process for water allocation and serve the needs of the farming community in the region. The information may also help in the better management of the recharge zones for sustainable management of those water resources.

\(^1\) The term agricultural refers to annual crops, horticulture, pasture and viticulture.
The hydrogeology and the recharge mechanisms of the groundwater system in the Moutere region have been studied quite extensively. Thomas (1989) inferred and mapped the main recharge zone for the deep Moutere aquifers as the Rosedale hills\(^2\) and similar conclusions were also confirmed in the work of Stewart and Thomas (2002) and Davie \textit{et al.} (2003). The evidence for this conclusion is the higher permeability of the Rosedale gravels, potentiometric surveys of borewells in the Moutere valley which indicated a flow direction from Rosedale hills, the age of the groundwater based on chemistry and isotope studies, and application of a hybrid dynamic neurofuzzy recharge model to understand links within the system (Davie \textit{et al.}, 2003). Part of the recharge zone falls within the Motueka River catchment but due to the presence of the Separation Point granite the infiltrating water is moving across the surface water catchment boundary into the Moutere aquifers (Figure 3.1 and 3.9).

Groundwater recharge to the Moutere aquifers from the Rosedale Hills has been estimated through a catchment water balance study conducted under two main land covers \textit{viz.}, pasture and \textit{Pinus radiata} (Davie \textit{et al.}, 2003). The study revealed that under the present land cover of Rosedale Hills the groundwater recharge results upscaled from small study catchments is quite low but it was hypothesized that diffuse low infiltration over a large area of the whole Rosedale Hills could add large volumes of water to the deep aquifers in the Moutere region. The Rosedale Hills is mainly covered by impermeable clay leading to rapid runoff and therefore no significant recharge except from incident rainfall. However, the water balance study did not include the wetlands located within the Rosedale Hills which could be playing a pivotal role in recharging the aquifers in Moutere region. The support for this hypothesis is the generalization that wetlands replenish aquifers located within the recharge zone of those aquifers (Winter and Rosenberry, 1995; Winter, 1999; Acreman and Bullock, 2003; Schot and Winter, 2006; Todd, 2006). However, studies also show wetlands may act as discharge zones due to geological, topographical, vegetation and climatic factors (Gilvear \textit{et al.}, 1993; Gilvear \textit{et al.}, 1997; Drexler \textit{et al.}, 1999; Raisin \textit{et al.}, 1999; Acreman and Bullock, 2003).

\(^2\) Waiwerho and Orinoco catchments together drain from the Rosedale hills.
The Waihero wetland (16 ha) is one of the largest wetlands in the Rosedale hills recharge area for the Moutere aquifers. It has an extensive cover of *Salix fragilis L.* (crack willow) and other hydric shrubs. Apart from the importance of willows for restoration/reclamation/management of some wetlands, serious concerns have been raised in the recent past about their effects on water resources due to high transpiration losses (Van Kraayenoord *et al.*, 1995; Stanley and Ward, 2003). Most of the willow tree species use large quantities of water through transpiration, reducing the freshwater availability for other in-stream and out-of-stream users. Both short-rotation coppice and naturally grown willows in riparian regions have high transpiration rates (Cermak *et al.*, 1984; Hall *et al.*, 1998; ARMCANZ, 2000; Schaeffer *et al.*, 2000; Doody *et al.*, 2006). However there are no reliable estimates of transpiration rates for crack willow, which could be used in modelling the water use of the tree species. Most of the regional councils in New Zealand require accurate water budgets for catchments and rivers due to the increasing human demand for fresh water particularly for irrigation. Thus it is important to understand the transpiration rates of crack willows particularly in summer, when the demand for fresh water is quite high.

In the present study the Waihero wetland is hypothesised to be providing groundwater recharge for the Moutere aquifers, being located within the potential recharge area. However the conflicting evidence by some studies showing wetlands as discharge zones due to geological settings and make the wetland a potential discharge zone. The overall aim of the present study is to establish whether the stated hypothesis above of the Waihero wetland as a groundwater recharge zone is correct, or whether it is a discharge zone. This will be done by determining the groundwater flux of the wetland.

The specific objectives of the study are:

1. To study the transpiration rate of crack willow across the seasons.

2. To conduct a wetland water balance for two summer seasons to understand the groundwater flux.
In the Motueka River tensions exist between in-stream users (recreational trout fishery), out-of-stream users (farming community) and local community (e.g., Maori) for water allocation during low flow periods of summer (Fenemor et al., 2006; Fenemor and Sinner, 2006). Currently there are limits imposed on water extraction from the Motueka River, for example under the Motueka River Water Conservation Order, so if more water is available in this Motueka River subcatchment, the regional council (Tasman District Council) may be able to adjust its water allocation limits there. This thesis aims to provide information to aid in this decision-making.
CHAPTER 2

2. REVIEW OF LITERATURE

2.1 Introduction of wetlands

This chapter provides a review of the literature for the present study. It will start with a description of wetlands in New Zealand and infestation by crack willows, then briefly illustrate how willows could be affecting the hydrological cycle and in particular groundwater flux through high transpiration. Later the aspects of forest evapotranspiration, methods of forest transpiration estimation and comparison of various sap flow techniques will be reviewed. Then past wetland and ground water interaction studies will be discussed, concluding with a review of wetland hydrology, a hydrological water balance and its components used in estimation of groundwater flux.

Wetlands are some of the world’s most productive environments and have important conservation, ecological, aesthetic, biodiversity and economic value. They provide benefits like water storage, flood mitigation, groundwater recharge, sediment stabilization, regulation of low flow, improved water quality and natural retention of some pollutants and nutrients (Clarkson et al., 2004). These systems are increasingly threatened by human pressure which has led to the disappearance of a large proportion of the world’s wetlands with mainly draining of wetland for agriculture. Today many wetlands are covered by aggressive weed-type phreatophytic vegetation with the ability to colonise stream beds with ease which causes severe problems in water management. The importance of wetlands and the pressures on them has prompted resource managers to develop means for their sustainable management. To do this effectively it is important to understand the behaviour of wetlands, particularly in eco-hydrological terms (Bullock and Acreman, 2003; Eamus et al., 2006).
Under the 1972 Convention on Wetlands, signed at Ramsar, Iran (and commonly referred to as the Ramsar convention) wetlands are defined as “areas of marsh, fen, peat land or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salt, including areas of marine water the depth of which at low tide does not exceed six metres.” (Article 1.1) and “may incorporate riparian and coastal zones adjacent to the wetlands, and islands or bodies of marine water deeper than six metres at low tide lying within the wetlands” (Article 2.1). Generally speaking ‘wetland’ is an area where water occurs at or near the land surface for a part or all of the year. The position of the water table causes the soil to be in a condition close to saturation during this time.

2.1.1 Wetlands in New Zealand

Wetlands are found throughout the country and the distribution is not uniform. Saline/estuarine wetlands are found throughout the country, montane wetlands are generally concentrated in the South Island and peat lands mainly in the North Island (Cromarty and Scott, 1995).

Wetland ecosystems are increasingly threatened by anthropogenic pressure and there is a considerable history of modification and use of wetlands by both Maori and Europeans. Large extents of fertile lowland and hill country are used for agriculture and forestry for which the conversion of wetlands has sometimes been significant. There are large regional variations in the rate of degradation of wetlands. For example, regions like Southland and Westland have retained more wetlands in better condition than those in Canterbury or the Bay of Plenty. Kahikatea swamp forest or ephemeral dune wetlands have been affected more than mountain bogs and tarts (Cromarty and Scott, 1995; Gerbeaux, 2002).

Presently, wetlands occupy less than 2% of the total land area of New Zealand. It is said that in the last hundred years some unique New Zealand wetland types have been lost and very few of them are left (Cromarty and Scott, 1995; Gerbeaux, 2002). The degree of wetland loss in New Zealand is about 90%, one of the highest rates in the world (Preece, 2002).
The New Zealand wetland classification by Johnson and Gerbeaux (2004) starts with a broad hydrological and landform setting of the hydrosystem, moving down to wetland classes based on substrate, water regime, and chemistry and finally to the lowest classification levels where vegetation becomes a defining factor.

At Level I nine hydrosystems are recognised based on general landform and broad hydrological settings, as well as distinctive features of water chemistry, salinity and temperature. The four important ones for wetlands are estuarine (coast), riverine (river), lacustrine (lakes) and palustrine (land). The other five systems are localised with low occurrences and therefore of less relevance to freshwater wetland themes. Level II comprises the nine wetland classes and may belong to one or more hydrosystems (e.g., fen, swamp, marsh, bog). Wetland classes are classified based on combination of substrate factors, water regime, nutrient status and pH. Level III structural class is concerned with the general growth form or structure of the vegetation (e.g., rushland, herbfield, sedgeland, shrubland) or the main type of ground surface (e.g., rockfield, mudflat). Level IV describes composition of vegetation allowing wetland types to be named from one or more dominant plants in combination with a structural class (e.g., bog pine, wire rush) (Johnson and Gerbeaux, 2004).

2.2 Crack willow

The spread of *Salix fragilis* L. (crack willow) in the wetlands of New Zealand and other parts of the world has been a major environmental problem in relation to health of wetlands. It is one of the weediest willow species in Australasia, and threatens many wetland and riparian sites (ARMCANZ 2000). This has led to the displacement of native plant communities, forcing changes to wetland habitat, affecting the native fauna and raising problems related to water management. Currently huge investment would be required to reclaim wetlands infested with willow trees to their original condition.

*Salix*, Latin for ‘willow’ is derived from the celtic word *sallies* (sal ‘near’ and lis ‘water’). *Salix* is one of four genera in the family salicaceae, and is thought to have
around 400 species. The willows are often divided into three subgenera: Salix (Amerina) (tree willows); Caprisalix (Vetrix) (shrub willows – sallows and osiers) and Chamaetia (dwarf, creeping, arctic or alpine willows) (Newsholme, 1992). These dioecious trees and shrubs originate from northern temperate regions. No members of the salicaceae are native to New Zealand but at least eleven species of Salix and five hybrids are naturalized (Webb et al., 1988).

The willow species occupying the study wetland is Salix fragilis with the common name crack willow. It is named crack willow because of the noise the wood makes when broken. It is a polycormic tree, widely distributed throughout Europe, the Middle East, and eastern North America (Newsholme, 1992). It is now found extensively in the Southern Hemisphere including New Zealand and Australia. It was first introduced to New Zealand in the early period of European settlement, and first recorded as naturalized in 1879 (Van Kraayenoord et al., 1995). Crack willow natural habitat is swamps, along riverbanks and other wet areas.

Most of the willow species are highly regarded for their physiological adaptations and ecological resilience (SRCMA, 2007). The main reasons for the spread of willows are their active vegetative reproduction. Willows are used extensively in ecosystem restoration work as they prove to be cost-effective. The unique physiological characteristics of willows making them suitable for use in ecosystem restoration work are as follows (ARMCANZ, 2000; Kuzovkina and Quigley 2005; Phillips and Daly, 2008).

- Ease of vegetative propagation
- Production of easily dispersible seeds
- Ability of seeds to germinate and survive in highly saline soils
- Ability of seedlings to tolerate both desiccation and inundation
- Tolerance of flood and oxygen shortage in the root zone
- Superior growth and high productivity even at early stages of establishment
- Extensive fibrous root system for bank stability
- Ability to accumulate high levels of toxic metals to be used for phyto-remediation
Willows are used for a wide range of purposes/management in New Zealand as follows (ARMCANZ, 2000; Kuzovkina and Quigley, 2005).

- River bank stabilization
- Reclamation of disturbed landscapes
- Wind breaks and shelter belts
- Used for landscaping due to aesthetic appeal
- Phyto-remediation
- Bioengineering
- Erosion control
- Biomass production
- To provide shade and organic source for aquatic fauna along water ways
- Habitat for birds
- Source of pollen for honey bees
- Supplementary fodder for domestic animals during dry periods

The detrimental impacts of invading willows on riparian areas are as follows (Van Kraayenoord et al., 1995; ARMCANZ, 2000; Stanley and Ward, 2003).

- Modification of stream morphology, hydrology and stability causing blockages/diversions
- Obstruction and diversion of river flows into river banks and threaten infrastructure
- Displacement of native vegetation and impacting biodiversity.
- High transpiration rates
- Increased bank erosion and decreased flood capacity
- Accumulation of fine silt in the river bed around root masses
- Reduced habitat availability on river bed for aquatic fauna
- Alterations to ecological processes due to change in nutrient cycling
- Reduction in amenity values by reduced access for canoeists and swimming holes

The aggressive growth of willows and their ability to colonise river and stream beds with ease has been shown to cause significant problems on the morphology of the river, aquatic health of streams and other detrimental impacts as listed above. *S. fragilis* is presently regarded as an invasive weed across the globe and in New
Zealand threatens many wetland and riparian sites. It is spreading in countries other than New Zealand, including Australia, South Africa and Canada (Cremer, 1999; ARMCA NZ, 2000). Concern in Australia has been sufficient for crack willow and most of the other willow species to be declared Weeds of National Significance, and a National Willow Strategic Plan has been developed for their management (ARMCA NZ, 2000). In New Zealand seven of 13 Department of Conservation (DOC) conservancies regard it as one of the top 10 environmental weeds in their conservancy (Roy et al., 1998; Froude, 2002). Similarly it is categorized as a weed in most countries. Biosecurity New Zealand and most of the regional councils in New Zealand manage for their adverse impacts and spend many thousands of dollars clearing them. However vast areas of wetlands and riparian region are still covered by willows and it is invading other areas in the country.

The above listed possible beneficial purposes may be outweighed by the problems raised by invading willows and it has been suggested to stop using willows for ecosystem restoration work in possible situations (ARMCA NZ, 2000; SRCMA, 2007). However it is acknowledged that willows can be beneficial in certain situations and landscapes, and also it is not possible to totally eradicate them given their unique physiological characteristics. It is a contentious issue and the restrictions of using willows are strongly opposed by river managers and engineers. Currently only willows are able to provide a low cost, effective tool for rapidly stabilising riverbanks and restoration of degraded lands (Stanley, 2002). Willows are still used for river management by regional councils in New Zealand though they are considered one among the top 10 weeds by the councils (Peter Williams, Landcare Research, pers. comm.). The River Managers’ Group is encouraging river engineers to look at alternatives to willows, including native species (Stanley, 2002; Phillips and Daly, 2008). However their reputed high transpiration leading to shortage of fresh water availability is still not considered seriously by the councils in New Zealand. Therefore it is important to understand its water use rates and help the councils in making better decisions in usage of willows in their programmes.
2.2.1 Effect of sawfly on crack willow

The options of biological control are considered seriously to control the spread of willow species causing serious environmental degradation of riparian and wetland habitats in the last few decades. The arrival of *Nematus oligospilus* Förster (Hymenoptera: Tenthredinidae), a sawfly that feeds exclusively on willows, was discovered in Auckland in February 1997 (Berry, 1997). Large numbers of sawflies were found to be damaging several different willow types and one among the main species is crack willow. The larvae are external leaf-feeders, with a demonstrated ability to defoliate and even kill the willow trees. Although the pest started from the North Island, in the last few years it has established in the South Island. It is assumed to pose a threat to soil stabilization and river bank erosion control programmes, which relies mainly on few willow species. There is also a growing realization of the long-term risk of pests in using a single species for river bank plantings (Phillips and Daly, 2008). However, wetland conservation groups, looking at the crack willow as a weed strongly feel sawfly could help in controlling willow distribution. The implications of the sawfly larvae on the success of willow control are unclear. It is unknown at this stage whether willow control will be made easier or more difficult as sawfly presence may impact on the capacity of the plants to take up herbicide. Studies on introducing other such biological controls are still being considered seriously (Harman, 2004; Adair *et al.*, 2006).

2.3 Transpiration

2.3.1 Forest transpiration

Transpiration by trees is a key element in the water use of forest stands. Availability of soil water, in the soil-plant-atmosphere system is one of the most important factors controlling the distribution and growth of forest trees. Water affects all phases of tree growth, because it is involved in various vital processes such as photosynthesis, respiration, transportation of minerals from soil, enzymatic activity, plant metabolism and physical support (Boyer and Kramer, 1995; Pessarakli, 2005).

The loss of water from plants in the form of vapour through the stomata (small openings in the leaf surfaces) is called transpiration. The rate of transpiration is
dependent on atmospheric conditions, water supply and plant species. Several hundred grams of water are required to produce a gram of plant dry matter and about 95% of this is lost as transpiration in this production process (Boyer and Kramer, 1995). Transpiration within intercellular spaces provides the cooling mechanism that allows plants to maintain the favourable temperatures necessary for metabolic processes.

Water deficits reduce tree growth and various other essential physiological processes. In warm sunny weather, transpiration often causes transient midday wilting and as the soil dries it causes permanent wilting and finally death by dehydration, if the soil moisture is not replenished by rain or irrigation (Boyer and Kramer, 1995). Many plant species close stomata during warm mid-day periods, when the transpiration rate exceeds the rate of water absorption by the roots (Saugier et al., 1997; Oren et al., 1999; Pataki et al., 200; Gazal et al., 2006). Pessarakli (2005) explains the midday depression due to high net radiation, VPD and low humidity causing stomatal closure and due to which there is low photosynthetic activity. He goes on further to explain how these factors are interlinked, affecting the physiological and biochemical processes of the tree lowering its productivity.

The total water loss to the atmosphere through transpiration combined with evaporation from the soil and wet plant surfaces (interception) is called evapotranspiration. It is well understood that interception loss in forested areas is more than that for pasture due to the canopy structure and meteorological factors thus leading to overall high evapotranspiration rates in forested areas (Davie, 2008). The ratio of transpiration to interception varies considerably depending on water availability. In tropical areas transpiration is dominant with high water supply and incoming solar radiation. The forest evaporation study by Grelle et al. (1997) in forests of Norunda, Sweden showed that roughly 70% of total evaporation was contributed by transpiration, 20% through interception evaporation (i.e. water evaporating from wet leaves following rainfall) and less than 10% from the forest floor. Many such studies on forest evaporation provided similar results (Grip et al., 1989; Kelliiher et al., 1993; Persson and Lindroth, 1994; Yaseef et al., 2010).
2.3.2 Transpiration by willow trees

A characteristic of most of the willow tree species is a capability to consume large quantities of water through transpiration and hence reduce the freshwater availability for other in-stream and out-of-stream purposes (Hall et al., 1998; ARMCANZ, 2000; Doody et al., 2006).

Most of the transpiration studies on willow tree species have been conducted in Europe and the temperate northern hemisphere using short-rotation coppice with a short cutting cycle. The studies showed high water use by willow stands of 8 to 10 mm/day, which is generally more than twice the estimated potential evapotranspiration (PET) of open water (Grip et al., 1989; Lindroth et al., 1994; Hall et al., 1998). Maximum daily evapotranspiration rates of 8-9 mm were estimated for coppiced short-rotation *Salix viminalis* plantations three hectares in area at Ultuna, Sweden by Persson and Lindroth (1994). Hall et al. (1998) in their study at Hunstrete, England compared different sap flow methods for a willow clonal plantation (10 ha) and found transpiration rates between 8 to 10 mm/day during the maximum leaf area period, which coincided with the highest values of net radiation and large humidity deficits. It is well established that high rates of biomass production mean high water consumption, causing reduced surface flow and groundwater recharge (Lindroth et al., 1994; Persson and Lindroth, 1994).

Similarly, the few studies on naturally grown willows in riparian regions have also shown high transpiration rates. The study on *Salix goodingii* (Schaeffer et al., 2000) growing along the perennially flowing San Pedro River, USA (South-eastern Arizona) and *Salix alba* (Lambs and Muller, 2002) growing on the active floodplain of Garonne river basin, France both transpired around 5.0 mm/day under varying environmental conditions. The study by Doody et al. (2006) on *Salix babylonica* transpiration in Yanco Creek system of New South Wales, Australia showed transpiration to reach a peak of 15.2 mm/day and the December month average was 12.0 mm/day. They found transpiration rates of willows in the creek bed was about six times higher, on average, than those growing on the bank (not having unlimited access to water). Similarly a two day transpiration estimation using the tissue heat-balance method in 1978 on two stems of crack willow in sedge-grass marsh (wetland) of Czechoslovakia
showed water use of more than 4.1 mm/day (Cermak et al., 1984). All these studies show that transpiration rates for willow tree species were high. However there are no reliable estimates of transpiration rates by crack willow, which could be used in modelling the water use of the tree species. The only study done on crack willow by Cermak et al. (1984) in Czechoslovakia was for two days on two stems and does not account for the variation across the seasons and tree size class in wetland conditions. The present study will cover this gap by conducting a year long sap flow study on crack willow trees in a wetland.

There are also studies showing evapotranspiration of willow tree stands in wetlands to be higher than other tree species. The study of evapotranspiration by different trees species in western USA Rivers by Nagler et al. (2005) showed the highest annual (1200 mm) transpiration by a willow and cottonwood stand. Evapotranspiration for other tree species (mesquite, saltcedar, giant sacaton and arrowweed) was less than 1000 mm/year. Similarly, Lambs and Muller (2002) found transpiration of willows higher than cottonwood tree species along the flood plain of Garonne River in France.

It is also understood that generally the transpiration of other wetland tree species is higher than those growing without an unlimited supply of water over the year. The study by Gazal et al. (2006) in the floodplain of the San Pedro River, south-eastern Arizona, USA found transpiration of riparian cotton wood in a perennial stream was 50% more than trees growing on an intermittent reach of the river. The daily transpiration of cottonwood trees in the perennial stream was 7 mm/day compared to 3 mm/day on intermittent reach. The study by Doody et al. (2006) on Salix babylonica showed peak transpiration of 15.2 mm/day for willows in the creek bed and a peak of 2.3 mm/day for those on bank without unlimited access to water. The wide literature on transpiration of tree species with water restriction due to change in season over the year show transpiration less than 5 mm/day for most of the tree species (Meinzer et al., 1995; Vertessy et al., 1995; Wullschleger et al., 1998).

2.3.3 Methods used in forest transpiration estimation
Measurement of water use by trees permits the partitioning of total stand evapotranspiration. In the last few decades the tree water use measurements have
become an important tool in micrometeorology, hydrology, agroforestry, tree physiology and horticulture (Wullschleger et al., 1998). Unfortunately, direct measurement of tree and stand transpiration in natural conditions is difficult due to their large size and heterogeneity. It is well known that estimation of evapotranspiration for forested vegetation is complex due to stem anatomy, canopy structure, organic floor, root systems and it significantly affects energy transfers between ground and the atmosphere (Shuttleworth, 1993; Granier, 1987). Due to various complexity of the site it is difficult to identify simple, direct and inexpensive techniques for determining transpiration of tree stands (Kaufmann and Kelliher, 1991).

Some of the methods used in measuring the transpiration of branch or single tree are plant chambers (Denmead et al., 1993), porometer (Dugas et al., 1993; Ansley et al., 1994), sap flow (Granier, 1987; Cermák et al., 1995) and chemical tracing (Kalma et al., 1998). There is another set of methods used in plant water use of tree stand estimation but these fail to provide information on the variation of transpiration among trees within a stand and they also include the evaporation from soil (Werk et al., 1988). These methods are the soil water budget (Nachabe et al., 2005), canopy transpiration models (Williams et al., 1996; Allen et al., 2000), Bowen ratio (Denmead et al., 1993) and eddy covariance (Baldocchi et al., 2000; Williams et al., 2004). All of the techniques listed above have merits and drawbacks with respect to their effectiveness at different spatial and temporal scales.

Plant chambers offer a method to measure water vapour exchange of whole plants, even including large trees, but they are not very portable and critically alter the microclimate of the plant (Denmead et al., 1993; Goulden and Field, 1994). It is also argued that estimates of water-use efficiency derived through plant chambers are effects of vapour pressure deficit (Lindroth and Cienciala, 1995). Determining transpiration from measurements of stomatal conductance made with a porometer is labour intensive and provides relatively poor time resolution (Dugas et al., 1993). In addition they are intrusive and also cause difficulties in calculating transpiration rates for leaves from measured stomatal conductances and aggregating these over the tree crown, while accounting for variations resulting from leaf age, illumination and boundary layer conductances (Ansley et al., 1994). Stable isotopes and deuterium are
commonly used as a tracer based technique for quantifying rates of water use, and overcome the limitations of using chemicals (tritium and $^{32}$P) due to increasing regulatory constraints. The data are difficult to interpret and the results only give mean values over periods of several days providing seasonal patterns (Calder et al., 1992). Plant weighing lysimeters are sensitive and provide high accuracy of water lost from the soil-plant system, but roots occupy a limited soil volume and lysimeters are expensive to maintain and construct. In contrast to other methods lysimeters provide total evapotranspiration and it is not possible to distinguish the transpiration (Chang, 2003). The main drawback of all the above techniques is technical difficulty in extrapolation of the transpiration rates measured on single tree to the stand level.

The plant water use of a tree stand estimated from the soil water budget is simple and provides information on the relative contribution of various rooting depths to the total transpiration source (Nachabe et al., 2005). It is acceptable only with accurate estimates of deep drainage loss, surface runoff and precipitation. The measurements are typically representative of only a small area and high spatial variability of soil water content results in sampling difficulties and problematic extrapolations to larger scales (Teskey and Sheriff, 1996). The various canopy transpiration models based on energy balance parameters are the most complex approach, too demanding for observed meteorological data and most assumptions go wrong. It is well understood that stomata exert considerable control on transpiration because canopies are tall, aerodynamically rough and well ventilated as opposed to crop plants (Jarvis and McNaughton, 1986). This has led to the conclusion that canopy transpiration models are appropriate for crop plants and not for tree stands as most assumptions are not met (Kaufmann and Kelliher, 1991). The commonly used micrometeorological methods, such as the Bowen ratio technique and eddy covariance provide high temporal resolution of tree stand transpiration but they are complex and expensive. Bowen ratio and eddy correlation have theoretical constraints that are difficult to satisfy in undulating, discontinuous forest terrain. Eddy covariance technique measurements are difficult to interpret during weakly turbulent periods and cannot directly account for advection in areas of heterogeneous or complex terrain, limiting its applicability (Baldocchi et al., 2000). All of the above listed methods fail to provide information on the variation of transpiration among trees within a stand and includes the
evaporation from soil. While some of them also include the evaporation from canopy interception (Werk et al., 1988).

Quick and effective ways of directly measuring the water flow through the xylem of a tree (sap flow), and thus whole-tree transpiration have been well developed and tested through various techniques (Cermak et al., 1973; Swanson and Whitfield, 1981; Granier, 1987; Hatton and Vertessy, 1990). Water moves by bulk flow in response to water potential gradients from the soil and in the tree xylem. When water transport occurs across membranes in the tree, the driving force is the water potential gradient across the membranes (Boyer and Kramer, 1995; Pessarakli, 2005). The main advantage of the sap flow method is that it provides measurements of transpiration for individual branches or trees, and helps in partitioning evapotranspiration between plant and soil evaporation and to divide estimates of transpiration among the component species of plant mixtures, which other techniques of evapotranspiration estimation lack (Kelliher et al., 1992). However it is important to note that estimates of water use derived from sap flow techniques suffer from uncertainties as a result of empirical calibrations, thermal gradients and radial sapwood variation in water flux, if the procedures are not followed correctly (Smith and Allen, 1996). Also an appropriate method of scaling from single tree to unit area of land (stand level) must be followed if the data are be used in hydrological studies (Vertessy et al., 1997; Wullschleger et al., 1998; Cermak et al., 2004). Sap flow methods are inexpensive, easily automated, provide high resolution and can be readily interfaced with data loggers for remote operation. Sap flow measurements are versatile because undulating terrain and spatial heterogeneity does not limit their applicability (Wilson et al., 2001). In contrast, determining transpiration through plant chambers, porometer or lysimeter is labour intensive, expensive and provides relatively poor time resolution information (Dugas et al., 1993).

The method of heat tracer to detect the movement of xylem sap flow was first developed and used by Huber (1932) (cited in Swanson and Whitfield, 1981). According to Edwards et al. (1996) the various methods developed in last few decades can be classified broadly into two main approaches viz., heat pulse and heat balance method. The heat pulse method uses the pulses of heat released in the sapwood as markers in the sap stream and heat balance method measures the
components of heat transport from a continuous heat input. The different techniques developed under the two approaches are listed in Table 2.1.

<table>
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<tr>
<th>Heat pulse</th>
<th>Heat balance</th>
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<tr>
<td>Heat dissipation (Granier, 1987; Oren et al., 1997)</td>
<td>Trunk segment heat balance (Cermak et al., 1973; Kucera, 1977, both cited in Cermak et al., 2004)</td>
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<tr>
<td>Heat field deformation (HFD) (Nadezhdina, 1998 cited in Cermak et al., 2004)</td>
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<td>Heat ratio (Burgess et al., 2001)</td>
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A detailed review of the above methods can be found in Swanson (1994); Edwards et al. (1996); Smith and Allen (1996); Čermák and Nadezhdina (1998); Kostner et al. (1998); Wullschleger et al. (1998); Burgess et al. (2001); Cermak et al. (2004).

The stem heat balance method can be used to measure sap flow in both woody and herbaceous stems of more than 4 mm diameter. Heat is applied to the entire circumference of the stem encircled by the heater and the mass flow of sap obtained from the balance of the fluxes of heat in and out of the heated section of stem (Sakuratani, 1981).

The trunk segment heat balance method follows a similar principle to the stem heat balance method but heat is applied internally to only a segment of the trunk making it practical for plant stems greater than 120 mm diameter (Smith and Allen, 1996). The heat field deformation method is based on measurement of deformation of the heat field around needle-like linear heaters, inserted into the stem. Sap flow is calculated from the ratio of temperature gradients around the linear heater in axial and tangential directions (Cermak et al., 2004).
The heat pulse velocity (HPV) method measures the velocity of the sap flow in the plant (sap conducting elements). In this method sap flow is measured by determining the velocity of a short pulse of heat carried by the moving sap stream, rather than the heat balance of a heated stem as described in most of the methods earlier. It is based on a compensation principle where the velocity of sap ascending a stem is determined by compensation of the measured velocity of a heat pulse for the dissipation of heat by conduction through the matrix of wood fibres, water and gas within the stem (Swanson, 1994). This method is suitable only for use on woody stems more than 30 mm in diameter. On the other hand it is not possible to use this technique on large trees where the full depth of sapwood cannot be accessed, as the sensor probes are installed by drilling holes into the sapwood in this technique. The main drawback of the HPV method is its inability to record low and reverse sap flow rates.

The heat dissipation method is an empirical method for measuring sap flow in trees developed by Granier (1987). Two cylindrical probes of 2 mm diameter are inserted into the stem, with one probe placed approximately 100 mm above the other. Constant power is applied to the heater and the difference in temperature between the two probes is then dependent on the rate of sap flow around the probes. Granier et al. (1990) observed that the technique does not depend on characteristics of wood anatomy and it is possible to use the method without calibration. As their claim is not derived from physical principles for heat transfer it is therefore recommended to be calibrated for species on which it has not previously been validated. However the major advantages of the thermal dissipation method are easy installation, simple instrumentation, straight forward sap flow calculations and inexpensive for which it is widely accepted and used (Smith and Allen, 1996).

The heat field deformation method is based on measurement of deformation of the heat field around a needle-like linear heater, inserted radially into the sapwood of the stem (Cermak et al., 2004). Sap flow is calculated from the ratio of temperature gradients around the linear heater in axial and tangential directions. The HFD method is highly sensitive to low sap flow rates, fast responding and has unique capabilities for measuring basipetal flows which occur during rain events after periods of drought when shoots are absorbing intercepted water or reversed flow in general (Burgess et
Detection of basipetal as well as low night re-saturating flows is important, because they carry valuable information about plant water status (Cermak et al., 2004).

Heat Ratio follows principles very similar to the HPV technique. However, it measures the ratio of the increase in temperature, following the release of a pulse of heat, at points equidistant downstream and upstream from a line of the heater, unlike the HPV technique. These improvements have helped in accurate measurements of zero, low and reverse sap flow rates (Burgess et al., 2001).

The heat pulse approach is widely accepted for its simple instrumentation, low cost, easy automation, readily interfaced, and most important its lower power requirements compared to heat balance methods (Green and Clothier, 1988; Edwards et al., 1996; Burgess et al., 2001). The improved version of the heat ratio method over the HPV method is regarded as more accurate. In addition the heat ratio method is capable of measuring low rates and direction of sap flow. The ability to measure low rates is important in studies concentrating on night and other periods of low transpiration rates. Similarly, the ability to measure low and reverse rates of flow accurately is critical to studies of hydraulic lift, hydraulic redistribution and root water uptake under dry conditions (Burgess et al., 2001).

### 2.4 Surface and ground water interaction in wetlands

Groundwater and surface water interactions in wetlands are mostly controlled by differences in head between the wetland surface water and groundwater. These in turn are controlled by local hydro-geomorphology, climate, catchment land use and wetland management (Rosenberry and Winter, 1997; Winter, 1999; McEwan et al., 2006). Groundwater and surface water interactions in wetlands are broadly classified into three flow regime types: (i) recharge (wetland loses water to the aquifer); (ii) discharge (wetland gains water from the aquifer); (iii) flow through (wetland gains and losses water based on spatial and temporal changes (Townley and Trefry, 2000; McEwan et al., 2006). On similar lines, a large number of wetland studies suggest that groundwater and surface water interactions in wetlands are highly dynamic, and both temporally and spatially complex.
An extensive review of 169 wetland hydrological studies by Bullock and Acreman (2003) found eighty percent of them concluding wetland involvement in alteration of water cycle as either a loss or gain. They found many studies with significant contrast, which are quite different from long-standing generalizations that wetlands always provide groundwater recharge, support low flow and abate floods. This was due to strong evidence of high evapotranspiration from wetlands thus leading to reduced dry season flows and ground water discharge to maintain wetland saturation. However they concluded by saying successful sustainable management of wetlands requires an understanding of their hydrological setting and it is difficult to transfer the knowledge gained from one to another; a point highlighted in other studies (Gilvear and Bradley (2000) and Acreman and Weng (2003).

The generalization that wetlands replenish aquifers, has been recognized as an important function of wetlands and many studies have provided results in that direction. The study conducted by Winter and Rosenberry (1995) in prairie pothole wetlands in North Dakota, USA showed that topographically high wetlands recharged ground water received from precipitation. Similar reasons for ground water recharge were also suggested by Winter (1999) and Schot and Winter (2006) in their discussion on various studies conducted across the globe. The study on ‘Depression-focused recharge’ in wetlands of south-western coastal plain of Argentina by Logan and Rudolph (1997) estimated ground water recharge rates at 40–60 mm/year in lower wetlands, whereas estimated recharge rates in the higher, drier areas ranged from 0–30 mm/year. These results were consistent with different methods used to estimate the recharge. Logan and Rudolph (1997) concluded by saying that standing water in local depressions of wetlands can lead to significant groundwater recharge. Similar results of ‘Depression-focused recharge’ were well documented for the clay-till plains of western Canada (Meyboom, 1966), kettle lakes of south-eastern Wisconsin (Cherkauer and Zager, 1989), and the Sandhills region of Nebraska (Winter, 1986). The significance of coupling wetlands with groundwater was demonstrated in upland wetland linkages and their roles in wetland recharge in the study by Todd (2006) in a large wetland (78 km²) dominated drainage basin in south central Ontario, Canada. They found recharge to be largely controlled by wetland position in the groundwater
flow system. All the above studies showed wetlands as recharge zones for ground water.

On the other hand there are many studies showing wetlands as groundwater discharge zones due to hydro-geological settings, high water table and high evapotranspiration. High variability among groundwater discharge rates for wetlands between seasons suggests that some sites are maintained largely by local-scale groundwater flow as opposed to regional flow as per the study of Drexler et al. (1999) in the McLean Preserve Fen (1.5 ha) in Freeville, New York. Their wetland was characterized by peat soils and groundwater inflow was 86% of the total wetland inflow. Similar results of high ground water inflow accounting for 97% of the surface water outflow, forming a dominant component in the water balance was found by Raisin et al. (1999) in the study of Reids wetland located in North-east Victoria, Australia. Surface water inflow and direct rainfall onto the wetland together contributed 3% of the surface outflow. Gilvear et al. (1993) in Badley Moor Fen of East Anglia, England showed the importance of local geology to the location of wetlands and evapotranspiration in supporting the discharge of ground water for maintaining the saturation of the wetland. The ground water discharge into the wetland accounted for about 90% of water inputs compared with only 10% through direct precipitation. Similar results were found in the study by Gilvear et al. (1997) in Carfield Fen around the same region (Norfolk Broads region) but ground water input to the wetland maintenance was small when compared to precipitation, evapotranspiration and surface water inflow. Though ground water inflow was low it was relatively constant over the year and flow was comparatively pronounced in summer due to high evapotranspiration and low rainfall. The Carfield Fen was hydrogeologically complex because a number of open drainage ditches missing thick peat layer cutting across its surface were acting as preferential pathways for ground water movement (Gilvear et al., 1997).

There is a third set of studies showing wetlands as both recharge and discharge zones dependent on seasons. The recharge-discharge function of most wetlands greatly changes both temporally and spatially due to various hydrogeological and climatic conditions. The study by Grapes et al. (2006) along the flood plain wetlands of the River Lambourn in central southern England showed large variability in recharge and discharge both in time and space. They noticed spring discharge in the upper
catchment and seepage flows from the chalk river to the alluvial aquifer. The study also revealed that effective recharge was exclusively in winter months, between October and March. Similarly, the vertical movement of ground and soil water in the wetland (within a tributary of Red River, North Dakota, USA) reversed several times seasonally in the study of Gerla and Matheney (1996). During the winter, water moved slowly upward in response to colder temperatures and frost near the surface. During late March to May thawing released water from vadose storage. This process, in combination with the infiltration of rainfall and snowmelt, caused hydraulic heads to rise rapidly near the water-table, thus producing recharge. Evapotranspiration, especially in mid-summer as precipitation rates decrease, caused shallow water levels to drop precipitously, thereby reversing the gradient again. In contrast to this, a small but potentially significant flow through the Everglades wetland (Florida, USA) recharged the aquifer and was stored for decades before being discharged back to surface water (Harvey et al., 2006). In some wetlands, there is a large difference in magnitude of recharge and discharge. This was found in the study of Choi and Harvey (2000), who tried to quantify ground-water recharge and discharge from Everglades wetland in northern Florida through a combined chloride mass balance and water balance approach. Over a 4-year period ground-water recharge averaged 9 mm/day and discharge was a meagre 0.9 mm/day.

There are a large number of studies pointing at evapotranspiration and especially transpiration of phreatophytic vegetation for the decrease in groundwater recharge or groundwater discharge into the wetland. The study by Meyboom (1966) in hummocky moraine of south-central Saskatchewan, Canada found groundwater reversal from recharge to discharge through the wetland due to high transpiration of willows. The wetland was mainly covered by willows (*Salix petiolaris*) and some of the higher grounds by aspen poplar (*Populus tremuloides*). The wetland was mainly acting as a recharge zone during winter, but later in the dry conditions there was ground water discharge into the wetland due to high transpiration of willows. It was believed that dry conditions and transpiration from phreatophytic vegetation had the capability of drawing ground water to the surface. Similarly, the study in a large (40,000 km²) alluvial fan located at the terminus of the Okavango River, Botswana showed how transpiration of phreatophytic vegetation lowered the water table creating a hydraulic head drawing groundwater towards the surface. During floods the water was captured
in the wetland and recharged the aquifers. Later in summer due to high evapotranspiration loss most of the wetland lost its surface water and phreatophytic vegetation drew water from the ground water reservoir (McCarthy, 2006). There are many studies showing the interference of phreatophytic vegetation especially willows in water management affecting the groundwater recharge from wetlands due to high transpiration (Meyboom, 1966; Cermak et al., 1984; Hall et al., 1998; ARMCANZ, 2000; Doody et al., 2006).

The present study will try to estimate the degree of groundwater flux (recharge or discharge) from a willow infested wetland, which lies within a hypothesized recharge zone.

2.4.1 Groundwater flux estimation

The fundamental water balance equation states that the amount water entering the wetland must be equal to the amount of water leaving the wetland plus the change in the amount of water stored (Figure 2.1). The water balance for a catchment or wetland is a study of the principle of the conservation of mass (water).

A general water balance equation to estimate the groundwater flux was written as follows (Owen, 1995):

\[
\text{Groundwater flux} = \text{Inputs} - \text{Outputs} \pm \Delta S
\]

Equation 2.1

Inputs = precipitation + surface inflow

Outputs = evapotranspiration + surface outflow

\(\Delta S\) = change in wetland water storage over time

Not all variables of the water balance equation occur in all wetlands and there are many different forms of this equation, all of which are broadly the same (Mitsch and Gosselink, 1993; Finch, 2001; Gippel, 2005; Bari and Smettem, 2006).
Groundwater flux\(^3\) in the equation will be estimated as “residual”, whereby all of the variables in the water balance model equation except ‘flux (recharge or discharge)’ are measured or estimated. The major limitation of the residual approach is that the accuracy of the flux estimate depends on the accuracy with which the other components in the water balance equation are measured or estimated. This limitation will be critical, when the magnitude of the flux rate is small relative to that of the other variables, in particular evapotranspiration and runoff, which are difficult to measure accurately. Even small inaccuracies can result in large uncertainties in the flux rates (Scanlon et al., 2002; Ranjan et al., 2006). The validation of the residual approach can be conducted through estimation of all the components in the water balance equation (Owen, 1995). However, this is not always possible due to the difficulties in making all the measurements, and therefore one component is calculated as residual of the water budget equation above.

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\(^3\) If the water balance (groundwater flux) results are positive then it is recharge and if negative it is groundwater discharge.
2.4.1.1 Precipitation

Precipitation is the easiest component in the wetland water balance equation to measure with least error when compared to other variables like evapotranspiration, runoff and change in soil water storage, although depending on the size of the wetland even precipitation can be error prone because of spatial variability.

Precipitation is water that reaches the earth from the atmosphere. The usual forms are rainfall, snowfall, hail, frost, fog and dew. Of all these, only the first two contribute significant amounts of water to earth and they vary temporally and spatially. In the present study most of precipitation is in the form of rainfall. There are two different types of raingauges used to measure rain viz., non-recording gauges and recording gauges. Non-recording gauges provide total depth of rainfall for a given time step (normally daily) and recording gauges provide additional information viz., time of occurrence, duration and intensity (Groisman et al., 1999).

Rainfall measurement errors in recording gauges are either random or systematic in nature (Sevruk, 1996). Random errors include those caused due to variation in topography, surrounding vegetation, aspect, altitude and human sources which increase the variability of a rainfall observation. Systematic errors are associated with factors such as wind effects, wetting, evaporation, splash, gauge inclination, geometry of the gauge, and possible nonlinearity between tipping rate and rainfall intensity. Random errors are easier to be overcome than the systematic errors (Chang, 2003).

There are various types of recording gauges and most widely used are the tipping-bucket type (Chang, 2003). The highest variation in tipping-bucket rain gauge measurement is due to random errors (variation in topography, surrounding vegetation, aspect, altitude and human sources) as per the studies of Sevruk (1996) and Heinemann et al. (2002). These errors are quite difficult to quantify and can cause inhomogeneous time series of rainfall observations if proper care is not taken. Tipping-bucket rain gauges are known to underestimate at higher intensities (>100 mm/h) because of the rainwater amount that is lost during the tipping movement of the buckets (Metcalf et al., 1997; Seibert and Morén, 1999; Molini et al., 2001; Molini et al., 2005). Currently the tipping-bucket rain gauge is the most commonly
used instrument for measuring rainfall in automated weather station networks due to the capability of automating the data collection process and eliminating the traditional human observer. During the last 20 years the tipping-bucket rain gauge has replaced almost every other type of rain gauge that had been used previously (Sadler and Busscher, 1989; Metcalfe et al., 1997).

2.4.1.2 Evapotranspiration

Evaporation is the process in which a liquid changes to the gaseous state at the free surface through the heat energy. It is the process by which water moves from the earth surface to the atmosphere. Evapotranspiration consists of both the movement of water through the plant to the atmosphere (transpiration), and water vapour from soil and water surface (evaporation) (Shuttleworth, 1993). Thus the entire surface and subsurface water released from a wetland into the atmosphere through the process of evaporation and transpiration is generally known as evapotranspiration. Important climatic parameters affecting the rate of evapotranspiration are solar radiation, air temperature, air humidity, atmospheric pressure and wind speed. The other factors which need to be considered when assessing the evapotranspiration process are the degree of shading of the crop canopy and the amount of water available at the evaporating surface. The driving force to remove water vapour from the evaporating surface is the difference between the water vapour pressure at the evaporating surface and that of the surrounding atmosphere (Allen et al., 2000). The greater the difference between the two vapour pressures the greater the evaporation rate. Crops predominately lose their water through stomata which are small openings on the plant leaf. Most of the water taken up is lost by transpiration and only a tiny fraction is used within the plant. Transpiration rate is also influenced by crop type, crop characteristics, water available for plant roots, environmental aspects and cultivation practices (Shuttleworth, 1993). Numerous studies have shown that evapotranspiration in forested watersheds is greater than that in non-forested watersheds and therefore higher crop coefficients are applied (Bari and Schofield, 1991; Finch, 1998; Zhang et al., 2001; Ranjan et al., 2006).

Evapotranspiration can be the largest term in the wetland water balance, dependent on season and water availability. In summer it is normally the largest due to high
incoming solar radiation and other supportive climatological drivers of evapotranspiration (Zhang et al., 2001; Nachabe et al., 2005). Unfortunately evapotranspiration is one of the water balance variables that is difficult to estimate accurately as it is an incidental, nonlinear, complex, unsteady process and involves a large number of climatological, topographical and landuse factors (Moghaddamnia et al., 2009). A slight error in estimation of evapotranspiration could lead to erroneous groundwater flux estimates using a residual approach to the catchment water balance equation (Diodato and Ceccarelli, 2006). Therefore it is very important to estimate the evapotranspiration precisely, since it is highly error prone and the largest parameter of the wetland water balance equation during low flow period, which is of interest in the present study.

Evapotranspiration with sufficient moisture always available to completely meet the needs of vegetation fully covering the area including evaporation from the soil is called potential evapotranspiration. The real evapotranspiration occurring in a specific situation is called actual evapotranspiration (AET). That is when water supply is deficient or soil moisture content is below field capacity, evapotranspiration cannot proceed at the potential level. Thus, the actual evapotranspiration is only a fraction or equal to PET (Shuttleworth, 1993). However in the present study there will be very little difference between PET and AET as there is sufficient soil moisture available for evapotranspiration at the maximum level for wetland vegetation.

The evapotranspiration process for forested vegetation is complex due to canopy structure, organic floor and root systems forming a complex environment that significantly affects water and energy transfers between ground and the atmosphere (Shuttleworth, 1993). Other factors that complicate the evapotranspiration process in forests are boundary layer effects, the physiology of different species, leaf morphology and plant hydraulic conductance (Eamus et al., 2006). Some of the commonly used direct micro-meteorological methods in estimation of evapotranspiration for forested watersheds are canopy transpiration models (Allen et al., 2000; Chang, 2003), Bowen ratio (Denmead et al., 1993) and eddy covariance (Baldocchi et al., 2000; Williams et al., 2004). It is well understood that transpiration forms the major component of the evapotranspiration of a tree stand (Zhang et al., 2001; Nachabe et al., 2005). In this regard there are many methods used in precise
estimation of transpiration from single tree or branch and upscaled to stand level but involving technical difficulties. Some of these methods are plant chambers (Denmead et al., 1993), sap flow (Granier, 1987; Cermák et al., 1995) and chemical tracing (Kalma et al., 1998). Another commonly used method on a single tree is a soil water balance in lysimeters but it provides total evapotranspiration (Chang, 2003). It is important to note that all of the evapotranspiration and transpiration methods listed above (direct and in-direct) have specific inherent advantages and limitations as discussed in the earlier part of the chapter.

Many tree canopy transpiration model are used to calculate the water vapour loss from foliage. Some of the commonly used models are the Thornthwaite model, Penman model, Penman-Monteith model and the modified Penman-Monteith model by FAO (Chang, 2003; Allen et al., 2000). Models are demanding of observed meteorological data and involve large number of assumptions. The models have been improved significantly in last few decades and there has been considerable debate over the most appropriate procedures for estimating water vapour loss from forest canopies (Kaufmann and Kellihier, 1991). The assumption subject to greatest error is the degree to which the stomata control transpiration in tree species. It is well understood that stomata exert considerable control on transpiration because tree canopies are tall, aerodynamically rough and well ventilated as opposed to crop plants (Jarvis and McNaughton, 1986).

Evaporation of water largely depends on the energy available. The energy arriving at the surface must equal the energy leaving the surface for the same time period (Allen et al., 2000). This is the principle of energy conservation used for estimation of evapotranspiration. This principle can be applied for large and extensive surfaces of homogeneous vegetation to get reliable estimates. Measuring different forms of heat accurately requires a lot of instrumentation and is complex (Denmead et al., 1993; Allen et al., 2000).

The mass transfer method is based on Dalton’s law, according to which transfer of water vapour from an evaporating surface is proportional to the wind velocity and the vapour pressure deficit and commonly referred as the eddy covariance method. The approach considers the vertical movement of small parcels of air (eddies) above a
large homogeneous surface. These methods require accurate measurement of vapour pressure, air temperature, wind speed at different levels above the vegetation surface and are thus expensive. Therefore its application is restricted to primarily research situations (Allen et al., 2000; Wilson et al., 2001).

The alternative to stand-level measurements of evapotranspiration is to measure the transpiration of representative individual trees and extrapolate the same to obtain stand level estimates of transpiration (Granier, 1987; Cermák et al., 1995; Martin et al., 1997) using the tree sap flux method. In this method there are no assumptions about the topography of the site to determine the source of water vapour, since tree sap flux is measured directly. Secondly, the measurements can continue under any weather conditions and are not limited to a summer day. Finally the measurements of sap flow in individual trees make it possible to examine the components of stand-level transpiration, revealing the functional contributions of different classes of trees within the stand (Cermák et al., 1995; Vertessy et al., 1995; Arneth et al., 1996).

Plant chambers are used to estimate the transpiration of trees through the measurement of plant gas (CO₂) exchanges at leaf level or at canopy level (Denmead, 1984). For a plant chamber outside air is continuously blown at a known flow rate into the enclosure (e.g., a plastic balloon) where gas exchanges occur. The difference of both water vapour and CO₂ concentration between incoming and exiting air, measured by infrared gas analyzers, provides the estimation of transpiration. However plant chambers are criticized for changing the micro environment of the plant substantially. They change the canopy boundary layer, vapour pressure deficit, radiation budget and light penetration (Denmead, 1984; Lindroth and Cienciala, 1995; Alterio et al., 2006).

The tracer based technique for quantifying rates of tree water use is based on unique isotopic signals provided by water in the xylem (Ehleringer and Dawson, 1992; Dawson, 1996). The stable isotopes and deuterium are commonly used for tracers and overcome the limitations of using chemicals (tritium and ³²P) due to increasing regulatory constraints. The data is difficult to interpret and the results only give mean values over periods of several days providing seasonal patterns (Calder et al., 1992).
In lysimeters plants are grown in isolated tanks filled with either disturbed or undisturbed soil. Lysimeters measure the change in soil water storage and assume the residual is evapotranspiration. They provide high accuracy and small time periods such as an hour can be considered. Experiments where the growing conditions in a lysimeter do not perfectly match the natural environment immediately outside of the lysimeter (e.g. plant height and leaf area index), have resulted in severely erroneous and unrepresentative evapotranspiration estimations. Also the lysimeters are difficult to build, expensive, and their maintenance requires special care so they are therefore used for specific research purposes (Allen et al., 2000; Chang, 2003).

In summary, evapotranspiration of forested watersheds is the sum of forest transpiration, interception by forest canopy and soil evaporation:

\[
\text{Evapotranspiration} = \text{transpiration} + \text{interception} + \text{open water evaporation} + \text{soil evaporation}
\]

\[\text{Equation 2.2}\]

2.4.1.3 Soil evaporation

Soil evaporation is often a major component in the water balance of agricultural systems, sparse canopies and deciduous forest when compared to a closed canopy tree stand (Lafleur, 1992; Moore et al., 1996; Baldocchi et al., 2000). Estimates of soil evaporation in semi-arid conditions range from between 30 to more than 60% of the seasonal rainfall (Daamen et al., 1995; Wallace et al., 1995). The presence of a dense canopy modifies a number of factors that influence energy availability for soil evaporation. These factors include net radiation, soil water content, wind speed, temperature and humidity beneath the canopy, quantity of decomposing litter (Kondo and Saigusa, 1992). As soil dries the surface resistance increases and soil evaporation reduces and after a threshold it is unimportant (McJannet et al., 1996).

Most of the micro-meteorological techniques used in estimation of evapotranspiration include an actual soil evaporation component but cannot be distinguished (Jackson and Wallace, 1999). The most commonly used direct method for soil evaporation estimation is microlysimeters (Stroosnijder, 1987; Daamen et al., 1993). In this method small undisturbed samples are collected in rings of limited height, closed at
the bottom, weighed and reinstalled in the field. It is a labour intensive method and cannot be automated. It is also possible to use an open top chamber on bare cleared ground to get an estimate of soil evaporation.

In most studies the soil evaporation component of total evapotranspiration was less than 5% for closed canopy forests and hence neglected (Jones, 1992). But Iritz et al. (2001) in their study (Sweden) on a Salix viminalis clonal plantation (irrigated) recorded soil evaporation of 23% of total evapotranspiration. Similarly the evaporation from the forest floor of a broad-leaved forest accounted for 10 to 20% (Kelliher et al., 1992) and 25% of evapotranspiration for old-growth rainforest dominated by the conifer Dacrydium cupressinum (Barbour et al., 2005) in New Zealand. This shows soil evaporation in willow forests and forest floors in New Zealand could be a major component of annual evapotranspiration to be estimated.

2.4.1.4 Runoff

Runoff is usually distinguished as rapidly occurring surface runoff, slower moving interflow and even slower discharge as baseflow (Smakhtin, 2001). In other words runoff is a portion of precipitation reaching the soil surface which finds its way into the streams. Surface runoff or overland flow is the amount of rainfall moving over the surface of the soil to the stream without infiltrating into soil at any point. Interflow is water entering the streams after passing through a portion of the earth. Slow discharge of baseflow (sub-surface flow) is rainfall entering the earth and flowing along the gradient and entering the stream at some point. It is difficult to distinguish between baseflow contributed by rainfall, unconfined aquifers and other natural storages (Hewlett and Hibbert, 1967; Smakhtin, 2001). Also it is not easy to determine what component of the total flow can be considered as baseflow (Tallaksen, 1995; Finch, 1998; Hughes et al., 2003). However total runoff can normally be measured accurately compared to evapotranspiration estimation.

Runoff is mainly measured as stream discharge. There are various stream flow measurement techniques and broadly classified into two categories as direct and indirect methods (Herschy, 1995; Godley, 2002).
Direct methods
(a) Area-Velocity method
(b) Dilution techniques
(c) Electromagnetic method
(d) Ultrasonic method

Indirect methods
(a) Hydraulic structures, such as weirs, flumes and gated structures
(b) Slope-area method

The Area-Velocity method of discharge measurement consists of measuring the area of cross-section of the stream at a selected section and the velocity of flow using current meters through the cross-sectional area. The dilution method of flow measurement, also known as the chemical method depends upon the continuity principle applied to a tracer which is allowed to mix with the flow. The ultrasonic method is an area-velocity method with the average velocity measured using ultrasonic signals (Godley, 2002).

The conventional structures like notches, weirs and flumes are used widely in field conditions for discharge estimation of streams. The basic principle is that these structures provide a unique control section in the flow. At these structures, the discharge is a function of the water-surface elevation measured at a specified upstream location. The slope-area method is based on the resistance equation for uniform flow in an open channel. Empirical formulae (e.g. Manning’s formula) can be used to relate the depths at either ends of a reach to the discharge (Herschy, 1995).

Making continuous measurements of stream discharge is a difficult, time-consuming and costly procedure. The most widely used discharge measurement method is a combination of indirect and the direct area-velocity method (Boiten, 2000). In this method stage (water flow level in the stream) is recorded continuously at required intervals using various automatic instruments, which are inexpensive and easy to handle. Meanwhile a stage-discharge relationship called a rating curve is developed, where the discharge in the stream is related to the elevation of the water flow (stage) through a series of velocity and cross section measurements using a current meter.
Finally the continuous discharge of the stream is estimated by linking the continuously recorded stage with the rating curve (Herschy, 1995).

2.4.1.5 **Soil water storage and movements**

Soil moisture is one of the key parameters governing interactions between the atmosphere, land surface and groundwater because it affects the partitioning of incoming rainfall into surface runoff and subsurface infiltration. It is variable both spatially and temporally, and knowledge of it is important for understanding and predicting several environmental processes and especially groundwater recharge (Finch, 1998). Soil water storage variation is controlled by many factors, such as soil texture, vegetation, topography and geology. The proportion of rainfall bypassing the soil store is not easily determined (Buttafuoco and Castrignanò, 2005). Physically the soil is made up of soil particles, air spaces (partially or fully filled with water), organic matter and living organisms. Water in the soil resides within the soil pores and a typical soil will have about 50% of the pore space as water and 50% as air. Generally after rapid drainage has effectively ceased, the soil water content becomes relatively stable and the condition is referred to as field capacity (FAO, 1985). However in a wetland during most parts of the year the majority of the soil pores are filled with water. This is mainly because most of the wetlands broadly fall into the category that are permanently inundated and wetted by unregulated stream flows throughout the year linked to rainfall events (Gippel, 2005). They are typically located at low elevations, along the streams and therefore the wetland is moist all around the year, without much change in the soil water storage.

Soil water content is measured using quantitative methods (amount of water content) and qualitative methods (indication of how tightly the water is held by the soil particles). Quantitative methods include gravimetric soil sampling, neutron probe, dielectric constant and qualitative methods include porous blocks (Rowell, 1994). Usually soil water is measured as a proportion of the volume of the bulk soil and expressed in weight or volume basis.

The gravimetric soil sampling method is a direct technique for estimating the water content of the soil. The method involves drying of a soil sample in an oven to
determine the amount of water in the soil. It is a destructive method and mainly used to calibrate indirect methods such as neutron probe or di-electric constant methods (Rowell, 1994). The neutron probe method estimates the amount of water in a volume of soil by measuring the amount of hydrogen in the soil. When calibrated correctly it is considered among the most accurate methods for measuring soil water content. Neutron probes are inaccurate in measuring moisture in the top 50 mm or so of soil as neutrons escape. They are also costly, it takes time in getting the license, and training and storage are required (McGarry, 2006). The di-electric constant method measures the capacity of soil to transmit high frequency electro-magnetic waves, which are related to soil moisture content through calibration. This is based on the fact that dry soil has a di-electric value around 2 and that of water is 80, when measured between 30MHz and 1 GHz. The two main instruments developed based on the di-electric constant technique are Time Domain Reflectometry and Frequency Domain Reflectometry. Both these instruments unlike neutron probe do not use radioactive material and reduce the time consumed in licensing, training, monitoring and storage (McGarry, 2006). The qualitative methods mainly try to determine the plant water availability and not quantify the water contained in the soil. These instruments are mainly used in agricultural fields to set irrigation intervals in the most efficient manner (Rowell, 1994).

2.5 Summary

Those wetlands covered by aggressive weed type phreatophytic vegetation and particularly crack willows have the ability to colonise stream beds with ease, and to cause severe problems in water management. Most of the willow species are highly regarded for their physiological adaptations and ecological resilience but the problems raised by the invading willows have led to their ban in some situations. However it is a contentious issue and the restrictions of using willows are strongly opposed by some river managers and engineers. Currently only willows are able to provide a low cost, effective tool for rapidly stabilising riverbanks and restoration of degraded lands.

A characteristic of most of the willow tree species is a capability to consume large quantities of water through transpiration hence reducing freshwater availability for other in-stream and out of stream purposes. This capability of high transpiration by
Crack willows has not been considered seriously in New Zealand. However it becomes more relevant as water becomes fully allocated in some catchments, because it could potentially be a significant part of the local water balance. Therefore it is important to understand willow water use rates to help regional councils in making better decisions in usage of willows in their river and water management programmes.

Most of the transpiration studies showed high water use by short-rotation willow stands of 8 to 10 mm/day, which is generally more than twice the estimated PET. Currently there are no reliable estimates of transpiration rates by crack willow, which could be used in modelling the water use of the tree species. The only study done on crack willow was for two days on two stems and this does not account for the variation across the seasons and tree size class in wetland conditions. This shows the need for long term study on transpiration rates of crack willows.

The total water loss to the atmosphere through transpiration combined with evaporation from the soil and wet plant surfaces (interception) is called evapotranspiration. Transpiration by trees is a key element in the water use of forest stands. The rate of transpiration is dependent on atmospheric conditions, water supply and plant species. The various direct and in-direct techniques used in measurement of evapotranspiration viz., weighing lysimeters, plant chambers, sap flow, chemical tracing, soil water budget, canopy transpiration models and micro-meteorological Bowen ratio. All methods have specific inherent advantages and limitations introduced for each of the measurement techniques and selection of the method has to be made on intent of the experiment.

Quick and effective ways of directly measuring the water flow through the xylem of a tree (sap flow), and thus whole-tree transpiration have been well developed in last few decades. Among the various sap flow techniques the heat pulse approach is widely accepted for its simple instrumentation, low cost, easy automation, and can be readily interfaced with data loggers for remote operation and lower power requirements. However it is important to note that estimation of transpiration rates from sap flow techniques involves technical difficulties in selecting the appropriate method of scaling from single tree to unit area of land (stand level) to provide transpiration rates in mm/day for hydrological studies.
Groundwater and surface water interactions in wetlands are mostly controlled by local hydro-geomorphology, climate, catchment land use and wetland management. It is well understood that groundwater and surface water interactions in wetlands are highly dynamic, and both temporally and spatially complex. The long-standing generalizations that wetlands always provide groundwater recharge, support low flow, and abate floods are disproved in some of the studies in last few decades. A large number of studies point at evapotranspiration and especially transpiration of phreatophytic vegetation for reducing wetland groundwater recharge and in fact encourage groundwater discharge into the wetland. It is believed that transpiration from phreatophytic vegetation has the capability of drawing ground water to the surface. In this regard the present study will try to estimate the degree of groundwater flux (recharge or discharge) from a willow infested wetland, which lies within a hypothesized recharge zone for Moutere aquifers, through a water balance approach.

The fundamental water balance equation states that the amount of water entering the catchment must be equal to the amount of water leaving the catchment plus the change in the amount of water stored. In most studies groundwater flux is estimated as “residual” because it is the most difficult component to be measured directly using the water balance approach. The major limitation of the residual approach is that the accuracy of the flux estimate depends on the accuracy with which the other components in the water balance equation estimated. This limitation will be critical when the magnitude of the flux rate is small relative to that of the other variables, in particular evapotranspiration and runoff, which are difficult to measure accurately.
CHAPTER 3

3. STUDY SITE DESCRIPTION AND INSTRUMENTATION

This chapter presents the details of the physical environment mainly concentrating on geomorphology, hydrogeology and delineation of aquifers. It then provides details on climatic conditions of the study region in comparison with the Waihero wetland for the last few decades. The next main sub section details the study wetland formation, human influences on the wetland, wetland fauna and water flow network. Finally the chapter describes the wetland monitoring network with instrumentation of stream flow, rainfall and evapotranspiration for ground water recharge estimation.

The study area is a small wetland within the Motueka River catchment. Due to the hydro-geological linkages the wetland falls within the potential recharge area for the Moutere valley aquifers, with infiltrating water moving across the catchment. Therefore the site description chapter will start with the larger area of the Moutere valley and later with the study wetland.

3.1 Description of the study region (Moutere)

The Moutere valley is located near Motueka at the northern end of the South Island and its jurisdiction comes under Tasman District Council (TDC) (Figure 3.1). The Moutere valley (catchment) is roughly 30 km wide and extends 65 km from the headwaters of the Motueka catchment to Tasman Bay (Stewart and Thomas, 2002). The study region (Moutere valley) lies between latitude 41° 08' to 41° 20' S and longitude 172° 50' to 173° 05' E. Moutere valley lies between the Tasman Mountains and the ranges of east Nelson, with an area more than 120 km².
Figure 3.1 Location of Waihero study wetland, Motueka, New Zealand

Notes:
- The surface flow from the wetland catchment flows into the Motueka River, but falls in the recharge area of Lower Moutere aquifers. (Source: Basher et al., 2003).
- Location of Rosedale Hills in the map is blue coloured recharge area of Moutere aquifers.
In the Moutere most of the land cultivated before 1980 was under pastoral farming but since then has been converted to orchards. The intensification of agriculture is increasing the demand for irrigation. The main surface water supply for the region is Moutere River water and the New Zealand Company Ditch, which is a supplementary channel for the Moutere River constructed by the New Zealand Company during the 1850’s. However both water resources are fully allocated for irrigation during summer months (Thomas, 1989). TDC in its State of the Environment Report, 2000 said that water resources in the Moutere Valley were fully allocated in summer and therefore not able to meet the water demands. All this shows water availability to be an important natural resources management issue in the Moutere valley.

3.1.1 Geomorphology and hydrogeology

The Moutere Depression is filled with Late Miocene and early Pleistocene terrestrial gravels of the Tadmor Group. The valleys of the Waimea, Upper Motueka and Moutere rivers have been cut into Moutere Gravel, with these rivers depositing Quaternary terrestrial sediments (Johnston, 1982). Moutere Gravel contains predominantly Torlesse greywacke clasts. The clasts occur in a yellow-grey silty fine sand matrix, and are moderately weathered. Well rounded, quartzofeldspathic sandstone clasts in a brown weathered muddy sand matrix comprise the bulk of the gravel (Thomas, 1989; Davie et al., 2003).

Geological and geophysical investigations show the Moutere Valley as a NNE trending basinal basement structure. Surface mapping has enabled the recognition of two units of Moutere Gravel, the lower unit Moutere Gravel (tm1), and the upper unit Moutere Gravel (tm2). The lower unit Moutere Gravel (tm1) outcrops only in the southwest of the area and dips gently into the Moutere Valley. The lower unit Moutere Gravel is correlated with the basal Moutere Gravel unit (Thomas, 1989).

An oil exploration well drilled by Petrocorp in 1988 and several deep water bores in the Moutere valley encountered Early Cretaceous Separation Point Granite outcrops in the west and probably extended eastwards beneath the Cenozoic cover. The seismic reflection surveys by Petrocorp in 1987 showed that western margin is also faulted
but obscured by Cenozoic cover. Rocks of the Rotoroa Igneous Complex form the southwestern margin of the basin (Thomas, 1989).

Based on hydrogeological investigations, three aquifers have been delineated in the Moutere Valley: Deep Moutere Aquifer (DMA), Middle Moutere Aquifer (MMA) and Shallow Moutere Aquifer (SMA) (Figure 3.2). The transmissivity, permeability and yields improve significantly with depth, and these parameters are also seen to be strongly influenced by the basement topography. Yields improve northwards and north-westwards from Ruby Bay. The deeper aquifers have better yields than the shallow aquifers. A major fault identified from seismic analysis compartmentalizes the groundwater system in the area into the Western Groundwater Zone and Eastern Groundwater Zone. A precipitation-infiltration recharge model indicated that the principal recharge area for the DMA and MMA aquifers in Moutere region was occurring through the lower unit (tm1) Moutere Gravel (i.e., Rosedale Hills area) which outcrops along the southwest of the Moutere Valley (Thomas, 1989). However recent studies found that eastern hills slopes (tm2) on the Moutere River could be also providing rainfall recharge (Stewart and Thomas, 2002; Davie et al., 2003). It is understood that large extent of the potential recharge catchment area for the Moutere deeper aquifers falls in the Motueka river catchment with groundwater moving across the catchment due to Separation Point Granite (Stewart and Thomas, 2002; Davie et al., 2003).
Figure 3.2 Schematic recharge model for the Moutere aquifers (Source: Stewart and Thomas, 2002; Davie et al., 2003)
3.1.2 Climatic conditions

The climate in the larger Motueka Catchment comprising the study catchment is “cool and humid” with some of the highest sunshine hours for New Zealand (Basher et al., 2003). In general terms it tends to be sunny and mild, less windy than other areas of New Zealand, and prone to frost in sheltered areas. The study site is well sheltered from severe westerly storms by western ranges and greatly exposed to weather from the north and north-east (Basher et al., 2003).

A fully automated TDC climate station is located 4 km north-east of the study site (Figure 3.9). It was set up in 1995 by TDC and data are mainly used to estimate the PET for pasture. Hourly data were collected from 1995 to 2008 and used to calculate air temperature, solar radiation and PET. The climatic parameters were recorded using a ‘Campbell Scientific automated logger - CR10’ (Campbell Scientific Inc). Daily rainfall from 1995 to 2008 was collected from a rain gauge set by TDC, 3 km south of the study site upstream of the Waiwhero wetland creek. The comparison of the 14 years monthly average with study year (2008) for rainfall, air temperature, solar radiation and PET are presented in Figure 3.3 to 3.6. Similarly, sunshine hours, raised open pan evaporation and wind speed were collected from the NIWA open access database for Riwaka, Motueka (Latitude 41° 05' 52" S and Longitude 172° 58' 19" E) for the last few decades and presented in comparison with year 2008 (Figure 3.6 to 3.8).

The wetland study area is one of the lowest annual rainfall areas in the Motueka catchment with around 1000 mm/yr (Preece, 2002). Rainfall from the eastern tributaries to the Motueka River is around 1000 mm/yr and increases slightly towards the coast (1300 mm/yr) (Basher et al., 2003). The 14 year annual rainfall average for the TDC rain gauge was 1116 mm and for the study year (2008) it was slightly higher (1295 mm). The number of rainy days was highly variable within the Motueka catchment and averaged between 100 and 150 days/year (Basher et al., 2003). The 14 year average for number of rainy days for the TDC rain gauge was 110 days and for the study year (2008) it was 113 days. The comparison of the 14 year monthly rainfall summation with year 2008 in Figure 3.3 shows winter as the wet period and summer
as the dry period. The wettest month during the study period was July, and in contrast May received less than 4 mm rain (the driest month). However there was above average rain for April and the start of winter in May would not affect crops and transpiration of willow trees significantly. Secondly the study is mainly concentrating on the dry period (November to March), during which the rainfall trend was similar to the 14 year monthly rainfall, except for December which received slightly more rain.

![Bar graph showing monthly rainfall comparison between 1995-2008 and 2008](image)

**Figure 3.3 Comparison of the 14 year (1995-2008) monthly rainfall summation with year 2008 for study catchment**

In the Motueka catchment the temperatures are milder nearer the coast and decrease inland and with elevation. Annual days of air and ground frost also increase away from the coast (31 days) and with elevation (82 days) (Basher *et al.*, 2003). Because the study site is at lower elevation, summers are very warm and winters are mild compared to the upper reaches of the catchment with around 30 days of frost annually. A comparison of the 14 year mean monthly air temperature with 2008 is provided in Figure 3.4. The mean monthly air temperature for all the months during the study year was similar to 14 year average except for the month of January (less), February (more) and May (more). The 14 year mean annual air temperature at climate
station was 12.8°C and for year 2008 it was approximately same (12.7°C). The winter period (May to August) mean monthly temperature was approximately 8.0°C and summer period (December to March) it is around 18.0°C.

![Graph](image)

**Figure 3.4** Comparison of the 14 year (1995-2008) mean monthly air temperature with year 2008 at the TDC climatic station

The 14 year mean annual solar radiation recorded at the TDC climatic station was 14.9 MJ/m²/day and 14.6 for the 2008. The mean monthly solar radiation for 14 years along with year 2008 is presented in Figure 3.5. The solar radiation was slightly higher in the month of January and lower than November compared to the 14 year average.
The 14 year estimated mean annual PET for grassland at the TDC climate station was 2.2 mm/day and for 2008 it was 2.7 mm/day. The average PET for 14 years was 781 mm and for 2008 it was 975 mm. This shows the during study year PET was close to 200 mm more than that the 14 years average. The potential grass reference crop evapotranspiration was computed using the Penman-Monteith empirical equation. Details of the derivation of this equation can be found in Monteith and Unsworth (1990). Some of the recommendations suggested by Smith (1991) were included as they were standards for use throughout the world by the FAO. The difference in the 14 year mean monthly PET with 2008 is provided in Figure 3.6. The 15 year annual open pan evaporation (raised pan) at Riwaka, Motueka was 1087 mm and was strongly seasonal, with mean daily values ranging from 0.6 mm/day in June (winter period) to 5.5 mm/day in January (summer period). The 15 years (1979 to 1994) mean monthly pan evaporation is also presented in Figure 3.6 along with PET estimated for grassland at the TDC climate station. The pan evaporation rates are among the highest in the country due to the high number of sunshine hours and incoming solar radiation.
Sunshine hours for the region are among the highest in New Zealand averaging over 2400 hours at Riwaka (Basher et al., 2003). The comparison of 28 year monthly mean and maximum sunshine hours for Riwaka site is provided in Figure 3.7. The average sunshine hours for three decades was 6.48 hrs/day.
The 30 year mean monthly wind speed and that in 2008 were not highly variable across the seasons in Riwaka, Motueka (Figure 3.8). It was slightly lower (1.37 m/s in June) in winter and higher in summer (1.78 m/s in December). Similarly the wind speed under the crack willow canopy in the study wetland in 2008 was low towards the start of winter and high during the summer. On an average the wind speed under the canopy was around one-third of open land supporting low evapo-transpiration under the canopy. Due to the failure of the instrument the wind speed was not recorded for the month of September 2008 under the willow tree canopy.

![Wind Speed Comparison](image)

**Figure 3.8** Comparison of 28 years (1979 to 2007) mean monthly wind speed at Riwaka, Motueka in open land to under crack willow canopy of the study wetland for the year 2008

### 3.2 Study catchment area (wetland)

The study of groundwater recharge for the Moutere aquifers was carried out in the Waihero wetland, situated about 11 km south-west of Motueka, which falls within the potential recharge area (Rosedale Hills) of the Moutere aquifers (Stewart and Thomas, 2002; Davie et al., 2003). The wetland lies roughly between 41° 10' 30" to 41° 11' 30" S latitude and 172° 55' 00" to 172° 56' 20" E longitude, at an elevation of approximately 50 m above mean sea level. The Waihero wetland catchment area is around 17 km² and forms a small east tributary (stream channel) of the Motueka River (Figure. 3.9). This wetland comes under the TDC valuable wetlands project (Preece,
The Waiwhero wetland covers approximately 16 ha and is 1100 meters long formed along the stream channel just few hundred meters before the confluence with Motueka River (Figure 3.10). The wetland width is approximately > 200 m in the upper reaches and < 100 m in lower reaches. At the western margin of the catchment, the stream channel before joining the main Motueka, there is an area draining Separation Point Granite and most of the water infiltrating before this point will move across the catchment to the Moutere valley aquifers (Stewart and Thomas, 2002; Davie et al., 2003).
Figure 3.10 Waiwhero wetland with monitoring network of capacitance probes, rain gauges, evaporation pan and vegetation survey strip plots
The two major landuses in the Waiwhero catchment are *Pinus radiata* plantation and pastoral farming (Figure 3.9). Around 3 km above the study site on the Waiwhero stream, water flow was recorded for the catchment (3.79 km²) from 1994 to 1998. Mean flow was 57 l/s and specific discharge was 15 l/s/km² (discharge per unit area, calculated from mean flow). The mean annual low flow was 8.9 l/s, which was calculated as the average of each year’s minimum flow for the period of record (Basher *et al.*, 2003).

The Waiwhero wetland (≈16 ha) is one among a number of large wetlands in the potential recharge catchment area (Rosedale hills) for the Moutere aquifers. Preece (2002) suggested that the wetland formed because of poorly draining soils, low gradients, and impeded drainage. Another important reason could be the discontinuity between the Moutere Gravels and the Separation Point Granite which occurs roughly in the middle of the wetland. It is possible that groundwater in the Moutere gravels is forced to the surface by the impermeable nature of the Separation Point granite although the general groundwater flow direction in the Moutere Gravels is away from the Separation Point granite. Equally the wetland could provide a significant recharge area for the Moutere Gravels groundwater. One of the general objectives of this study is to attempt to decipher between the two conflicting wetland theories.

Based on the broad hydrological and landform setting classified by Johnson and Gerbeaux (2004), the hydrosystem of the wetland falls under the category of Palustrine with freshwater and dominated by emergent willow trees and a small fraction of other phreatophytic vegetation. Under the wetland class it falls into the category of swamp as the water sources include surface water inflow, possibly groundwater, rainwater and being wet all around the year. The main plant species are crack willow (*Salix fragilis*), cutty grass (*Carex geminata*), swamp coprosma (*Coprosma tenuicaulis*), manuka (*Leptospermum scoparium*), gorse (*Ulex europaeus*), himalayan honeysuckle (*Leycesteria formosa*) and New Zealand flax (*Phormium tenax*).

Crack willows cover more than 75 percent of the wetland area. In some parts of the wetland the understorey of willows and open water areas are covered by dense sedgeland. The main species of sedgeland is *Carex geminata*. A small area in the middle of the
wetland is covered by shrubland species of swamp coprosma, manuka and New Zealand flax.

Few other wetlands of similar features are found in close proximity to the study wetland. One of them is just above the confluence of the ‘forest’ inlet and Waiwhero wetland tributary. This wetland is surrounded by *Pinus radiata* plantation and managed by Carter Holt Harvey Company (Preece, 2002). Another close by wetland is found adjacent to Waiwhero road, owned privately by two families, which is less than 1 km to south west of study wetland.

### 3.2.1 Soils

Soils of the wetland are typically of low to moderate fertility and have clayey textured pale-coloured subsoils with impeded drainage (Preece, 2002). Catchment area is hilly terrain underlain by Moutere Gravels (tm1). The gravel has clast sizes ranging up to 150 mm, which occur in a yellow-grey silty fine sand matrix and moderately weathered. The Moutere Gravels have a transmissivity of 3 to 120 m$^3$/day/m (Thomas, 1989). The description of soils for the Waiwhero catchment was provided by Chittenden *et al.*, 1966 (cited in Thomas, 1989). Most of the catchment area of wetland was covered by Rosedale hill soils. A small part of the mid reaches, presently planted with *Pinus radiata* was formed of Rosedale silt loam, while the wetland valley and low lands are covered by Braeburn sandy loam. The soil towards the outlet of the wetland was formed by Sherry sand and sandy loam.

### 3.2.2 Wildlife in wetland

The wetland provides a habitat for some important fish and bird species and therefore is an important wetland with conservation status. The wetland provides habitat for Giant kokopu (*Galaxias argentus*), which comes under ‘Category B species’ of ‘high conservation status’. This fish is found in very few sites in Tasman Bay, but interestingly, several records of this fish were found in the wetland and also a few hundred metres upstream in Waiwhero (Preece, 2002 and James, 2006).
The wetland also is known to be home to the regionally vulnerable South Island fernbird (*Bowdleria punctata*). In the last few decades it was widely distributed in the Moutere wetlands but sightings in recent times have declined (Preece, 2002). Apart from the above listed vulnerable species, the wetland is habitat for many other bird and fish species.

### 3.2.3 Anthropogenic influences

Wetland ecosystems have been vulnerable to anthropogenic threats in last the 150 years with extensive settlement by Europeans (Clarkson *et al*., 2004; Cromarty and Scott, 1995; Gerbeaux, 2002). Prere (2000) found a nearly 60% decrease in palustrine wetlands across the Tasman District and in most intensively studied areas the decrease was more than 81%. Wetland loss particularly in privately owned land was more than 97%.

The Motueka and Moutere Ecological Districts are depleted to 65 ha of their original 3145 ha palustrine wetlands. The overall wetland loss with respect to all types in the Moutere Ecological district was approximately 93%. A total of about 40 wetlands are recorded from the Moutere Ecological district (Preece, 2002). The main reason provided for the decrease in wetland area in the region was human interferences.

The Waiwhero wetland had few willow trees a couple of decades ago and now is fully covered by crack willows. This has lead to the displacement of native plant communities, forcing changes to the wetland habitat and potentially affecting the native fauna, which rely on native plants for their survival. Currently huge investment would be required to reclaim the wetland to its original condition. The edges and some parts of the study wetland have been drained and converted to pasture. The wetland is privately owned by two families and has pasture and *Pinus radiata* plantation around the margins. In the lower part of the wetland cattle, sheep and goats graze on the pasture around the wetland and sometimes rely on the bark and succulent twigs of crack willow trees in the wetland. The upper part of the wetland is fully fenced and domestic animals are not allowed into the wetland.

The human induced land-use change pattern in the catchment could reduce stream flow and affect the water management and aquatic life in the wetland. Long term studies
conducted by Duncan (1980 and 1995) in the Moutere region of converting small (<10 ha) hill country catchments in pasture and gorse to Pinus radiata forest, and subsequent felling of the mature forest, showed significant changes in water yield and flow patterns, mainly due to changes in interception and evapotranspiration. Planting of Pinus radiata on pasture led to reduced flow and water yield, an increase in the number of days with no flow and reduction of peak flows. Gorse clearance also led to a decrease in the number of days with no flow, but an increase in the magnitude and persistence of low flows. Harvesting of Pinus radiata plantation increased base flow compared to pasture.

3.2.4 Wetland inflow network
The surface water inflow and outflow of the wetland is perennial but flow during dry spells in summer was a few litres per second. The only two other inlets, perennial in nature, were ‘forest’ and ‘north’ inlet as the catchment area was quite large. It is important to note that water flow of both the ‘main’ and ‘north’ inlets passes through various paddocks before reaching the wetland and is blocked at some places during dry periods by the land owners. On the other hand the Waiwhero wetland has many small ephemeral inlets other than the perennial inlets on rainy days and during the winter period. Based on this knowledge of wetland inflow the stream network monitoring was developed.

3.3 Wetland monitoring network
The wetland instrument network locations are shown in Figure 3.10.

3.3.1 Stream flow monitoring
The water flow level (stage height) for the three major inlets (main, forest and north) was recorded using Odyssey™ capacitance probes every 30 minutes for more than one year (2008 and 2009) covering two summer periods. Later the discharge was estimated based on rating curve. To develop the rating curve the flow was measured at different stage heights using an Ott current meter and the velocity-area method. The discharge for extreme low flows in summer was estimated using a bucket and stopwatch method, as the flow was quite low and it was not possible to use current meter (Hauer and Lamberti, 1996).
3.3.2 Wetland groundwater flux

A capacitance probe was installed in the middle of the wetland to understand the change in wetland storage and for the estimation of the wetland open water area.

3.3.3 Rainfall

Tipping-bucket rain gauges were used to record rainfall. Rainfall for the wetland was recorded on a flower bed around 100 metres above the main ‘inlet’ of the wetland. The data gaps in rainfall data collection were filled in from a nearby rain gauge maintained by TDC (Figure 3.9). Another rain gauge was set up under the canopy of the crack willows (beside the site for pan evaporation) to estimate the interception of the willow trees.

3.3.4 Evapotranspiration

To estimate the evaporation of the water under the canopy of crack willows, an automated Class A evaporation pan was installed close to the centre of the wetland. The weight of the evaporation pan (measured via load cells under the pan) was electronically monitored for a continuous record. It was supported by an anemometer to record wind speed. The data from the evaporation pan, anemometer and the rain gauge were all recorded by a Campbell CR10 automatic logger. The power was supplied through a solar panel.

3.3.5 Sap flow

The sap flow in the wetland was recorded on nine trees representing different tree size class distributions. The representative trees were chosen after conducting a vegetation survey. All the sap flow instruments were implanted on trees in the upper part of the wetland as it was fenced thus avoiding disturbance from the animals, whereas the lower part of the wetland was dominated by cattle and other small ruminants feeding on the bark and succulent twigs of willow trees. This animal activity could disrupt the sap flow instruments on the trees and therefore none of the willow trees in the lower part of the wetland were implanted with sap flow instruments.
3.3.6 Interferences with monitoring

The wetland was prone to incidence of wild pigs, rodents and possums but fortunately no major damage to the instruments was done except for a couple of minor incidents. Another threat was the fragile nature of polymeric crack willow trees. During strong winds a good number of willow trees would fall over and block access to some of the instruments but luckily none of the trees selected for sap flow measurement or any instruments installed for monitoring were destroyed directly from a falling tree. The only other unfortunate incident during the study period was the destruction of the rain gauge outside the wetland by the farmer, while mowing the grass.

Solar panels were not able to meet the demand of power for load cells of the evaporation pan in winter (May to August). Therefore a couple of external heavy batteries were installed to meet the energy demands of the ‘load cells’. This problem was mainly due to short winter days (few sunshine hours) compared to long summer days.
CHAPTER 4

4. METHODOLOGY

One of the stated objectives of the study was to estimate the groundwater flux in the wetland infested with crack willow through the water balance approach. The various components of the monitoring network for data acquisition were discussed briefly in the earlier site description chapter. The present chapter provides methods, data acquisition procedures and details of the experiments conducted in estimating the individual components of the water balance equation. It will begin with a description of the water balance approach used in estimating the groundwater flux. Then it will describe the method used in measuring precipitation, the main input of the water balance equation. Next it will discuss the sap flow technique used in estimating the transpiration of crack willow trees as a component of evapotranspiration for the wetland. It will start with an explanation of the tree selection method for sap flow study through a vegetation survey, and the sap flow instrumentation procedures. Later it will deal with the various errors involved in the sap flow techniques and the procedures followed to overcome them. In this direction various experiments were conducted viz., understanding radial variability of sap flow, determination of sap wood area, determination of low sap flow velocity, scaling methods and validation of the sap flow results, all discussed in detail with the results of the experiments. This will be followed by a discussion of the methods used in estimating interception loss and open water evaporation from the wetland, and the other components of evapotranspiration will be described. Finally the methods used in the estimation of surface water flow and groundwater level in the wetland are described, together with the other variables of the water balance equation.
Most of the data (precipitation, surface flow, groundwater level in the wetland and that from the evaporation pan) for the present study were collected from October 2007 to April 2009, covering two summer periods (2008 and 2009). The sap flow data for estimating transpiration of crack willows were collected between February 2008 and April 2009. The few months of missing data of sap flow and rainfall were generated using a simple regression model.

The water balance approach was adopted to understand the rate of groundwater flux from the wetland. The fundamental water balance equation states that the amount of water entering the soil must be equal to the amount of water leaving the soil plus the change in the amount of water stored in the soil (see equation 2.1).

It was advisable to measure or estimate all of the components of the water balance equation as it would help in reducing the magnitude of errors. However this is not always possible due to the difficulties in making hydrologic measurements and one component is often calculated as the residual of the water balance equation (Carter, 1986). In the present study, due to practical difficulties, the groundwater flux (recharge or discharge) in the equation was estimated as a residual, whereas all of the other variables in the water balance model equation were either measured or estimated.

### 4.1 Precipitation

Precipitation is the easiest component in the wetland water balance equation to measure with least error when compared to other variables like evapotranspiration, surface flow and change in soil water storage.

A self recording tipping-bucket rain gauge was used to measure rainfall in the present study. The few months gap in rainfall data was filled using rainfall measured by at a site operated by the Tasman District Council (TDC) less than 3 km to the south of study wetland (Figure 3.9). The regression provided an $r^2 = 0.96$ representing a strong linear relationship between available rainfall data for the wetland and the TDC rain gauges (Figure 4.1). The residuals of the regression were evenly distributed and showed the reliability of using the regression equation in filling the rainfall gap.
The half hourly rainfall data were looked at closely to understand the zero rainfall events at the wetland rain gauge, when it had rained at the TDC rain gauge and vice versa. In more than 65% of such events it was a true representation that it rained at one site and did not rain at other site. This was also confirmed from the wetland inflow data. The TDC rain gauge was located in the catchment area near the main wetland inlet. The water inflow volume increased for the main inlet but had not changed at the forestry culvert inlet (catchment area close to wetland). This confirms that it was raining at the TDC rain gauge and not around wetland area. Another factor causing this difference was midnight rain. Approximately 20% of the events were late night rain, with a few hours difference were showed on successive day for daily totals and corrected before conducting the regression.

![Linear regression relationship between daily rainfall collected by TDC, and by the wetland rain gauges](image)

**Figure 4.1 Linear regression relationship between daily rainfall collected by TDC, and by the wetland rain gauges**

### 4.2 Evapotranspiration

The evapotranspiration process for forested vegetation is complex due to canopy structure, organic floor and root systems forming a complex environment that significantly affects water and energy transfers between ground and the atmosphere (Shuttleworth, 1993, Whitley and Eamus, 2009). The major components of evapotranspiration for a forested wetland are the sum of tree transpiration, interception evaporation by the canopy, and soil
and open water evaporation (Equation 2.2). The present study attempts to measure the major components using different methods.

4.2.1 Transpiration

The transpiration of crack willows mainly covering the wetland was estimated through the heat pulse velocity sap flow technique. This technique is rapid, simple, of low cost, and practical to estimate whole-tree sap flow with due corrections for the variations of sap flow density (Hatton and Vertessy, 1990; Dye et al., 1991; Hatton et al., 1995; Phillips et al., 1996; Oren et al., 1999; Wullschleger and King, 2000). Although the newly developed heat ratio method sap flow technique would provide better estimates of low sap flow rates at night and in winter, the HPV technique was used for the present study as the instruments were already available at Landcare Research. Also it was well understood that night time transpiration is negligible (Benyon, 1999) and the present study was not concentrating on the low winter transpiration, and therefore the willow transpiration was measured using the HPV technique.

Heat Pulse Velocity (HPV) method

The HPV method measures the velocity of the sap flow in the tree xylem, which is based on a compensation principle. For the present study, Greenspan Sap flow Sensors (Model SF300, Greenspan Technology, Warwick, Australia) were used. Each sap flow sensor (probeset) consists of two thermistors, one 10 mm upstream (T_u) and one 5 mm downstream (T_d) from a heater. The sensors measure sap flow velocity at a point in the sapwood. Thermistors and heaters are enclosed in 2 mm diameter stainless steel tubing, and paired on the vertical plane to facilitate the measurement of sap flow velocities (Figure 4.2). The thermistors were smeared with petroleum jelly and implanted in parallel access holes drilled radially into the water-conducting wood (sapwood) using a 2 mm drill bit at breast height. A drill jig was used to ensure that the holes were correctly spaced and parallel to each other. Short periodic heat pulses released from the heater are recorded by the thermistors implanted upstream and downstream of the heater. Given the asymmetric spacing of the thermistors, T_u initially warms faster than the T_d because of conduction (diffusion) and there is a steep initial rise beginning at time T_1. In Figure 4.3 the difference in temperature between the T_u and T_d with change in time is presented graphically. The
temperature difference of the thermists (T_u-T_o) peaks, and then, as the heat pulse carried by the moving sap (convection) moves towards T_d, the difference between the two thermistor returns to baseline equilibrium at time T_2. If convection is occurring the temperature differential will become negative as T_u cools and T_d continues to warm for a time, but eventually once all the added heat leaves the system, thermal equilibrium is restored. The crucial value in the above cycle is the time taken to reach T_2, known as heat pulse time (T_o). The net distance travelled (d) by the heat pulse at this point, which has moved to a midpoint between the pair of thermists is equivalent to 2.5 mm. As the spacings between the thermitors are fixed, the logger only records the value of T_o at each sampling. The formula for heat pulse velocity (V_h) is as follows.

\[
V_h = \frac{X_u + X_d}{2T_o}
\]

Where X_u and X_d represent the distances of the thermists upstream (-5 mm) and downstream (10 mm) of the heater. A negative value is assigned to X_u because it is located upstream from the heater. T_o is the time taken for heat pulse time to travel from T_1 to T_2 in Figure 4.3. Sap flow velocity multiplied by the cross sectional conducting wood area gives the volume per unit time of transpired water.
Figure 4.2 Arrangement of Greenspan Sap flow Sensor with two thermistors ($T_u$ and $T_d$) and heater, implanted radially into a stem

Figure 4.3 Temperature difference between the upstream and downstream sensors ($T_u - T_d$) with change in time after the release of heat pulse from the heater
It was important to provide protective thermal insulation cover for the sap flow sensors to avoid any interference of solar radiation or rain with the temperature differences of the sensors (Anon, 1996; Smith and Allen, 1996; Becker, 1998). Therefore the tree trunk with sap flow sensors around the stem was covered with pink bats (household bats) used for home insulation (Plate 4.1). Later emergency thermal blankets (aluminium foil) were wrapped on the pink bats to act as radiation shield and avoid wetting of pink bat. Then the both the ends of the thermal blankets were sealed against the smoothed bark of the tree with duct tape tightly (Plate 4.2).

Plate 4.1 Thermal insulation provided to sap flow sensors using pink bats (household insulation bats)
Plate 4.2 Thermal blankets (aluminium foil) wrapped on the stem to act as a radiation shield and to avoid wetting of the pink bat, with both the ends sealed against the smoothed bark of the tree with duct tape.

The HPV method of sap flow estimation as explained above is based on integration of a set of point estimates of sap flow velocity in the sapwood of individual trees. Errors associated with estimation of stand transpiration arise from (a) the measurement and calculation of the point estimates of sap flow, (b) the integration of point estimates into a sap flow volume for a single tree and (c) the extrapolation of sap flow volume from sample trees to a stand and expressed on an areal basis (mm per unit area). Details of the above mentioned errors are described by Hatton et al. (1990), Hatton et al. (1995), Smith and Allen (1996), Vertessy et al. (1997), Nadezhdina et al. (2002) and Cermak et al. (2004). Later in the chapter, the details of errors involved in the HPV technique, and procedures followed to overcome them, are provided. Given the range of uncertainties in the HPV technique the results are validated using the cut tree experiment based on volumetric measurement of usage of water under field conditions.
4.2.1.1 Vegetation survey

Sap flow of a few sample trees representing the stand is measured and later scaled to the whole stand. It is suggested that selection of sample trees for sap flow measurement in a mixed stand needs to follow sampling across the tree size class to reduce the error in scaled stand transpiration (Granier et al., 1990; Hatton et al., 1995; Nadezhdina et al., 2002). Therefore it was important to understand the sampling intensity required to reduce the sampling error in estimation of transpiration and best possible use of resources.

The soil moisture varies considerably from the centre of the wetland to the edge, altering the vegetation structure and composition along the gradient. To include the variation of narrow landscapes along a stream in sampling the appropriate method would be strip plots randomly placed at right angles to the water flow to represent the study area (Husch, 2003) (Figure 3.10). Methods described by Husch (2003) and Czaplewski (2003) were used for vegetation sampling.

Each sampling strip plot was 10 m wide and the average area covered in each plot was close to 500 m². Assuming the population normal distribution (Figure 4.4) with a 90% confidence interval, and an allowable error of 10% of the mean, the number of sampling strip plots required was 10 for the size and variability of willow trees in the wetland. Sixteen such sampling strip plots covered a total of 8,000 m² (0.8 hectares) with a sampling intensity of 5.6%. The “extra” plots (i.e. 16 instead of 10) were introduced to lower the sample error. Total counts of individual trees of more than 5 cm in diameter and their corresponding diameter in each sample plot was recorded. Crack willow trees tiller from within the ground level making them polycormic trees. Each tiller was considered as an individual tree as it was difficult to locate the main tree and all the tillers in the strip plot irrespective of the main tree outside the plot were considered as sample plot population. The descriptive statistics of the vegetation sampling are provided in Table 4.1. The vegetation survey showed the mean diameter at breast height (dbh) of willow trees in the wetland was around 28 cm with a standard deviation of 4.5 cm. The tree density for the wetland was around 630 trees per hectare.
Table 4.1 Descriptive statistics of the vegetation sampling

<table>
<thead>
<tr>
<th>Plot number</th>
<th>Number of trees per plot</th>
<th>Mean dbh (cm)</th>
<th>Tree density (trees per ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>14</td>
<td>28</td>
<td>519</td>
</tr>
<tr>
<td>2</td>
<td>18</td>
<td>34</td>
<td>474</td>
</tr>
<tr>
<td>3</td>
<td>19</td>
<td>17</td>
<td>594</td>
</tr>
<tr>
<td>4</td>
<td>55</td>
<td>31</td>
<td>611</td>
</tr>
<tr>
<td>5</td>
<td>37</td>
<td>27</td>
<td>463</td>
</tr>
<tr>
<td>6</td>
<td>23</td>
<td>32</td>
<td>442</td>
</tr>
<tr>
<td>7</td>
<td>31</td>
<td>23</td>
<td>646</td>
</tr>
<tr>
<td>8</td>
<td>24</td>
<td>25</td>
<td>800</td>
</tr>
<tr>
<td>9</td>
<td>11</td>
<td>22</td>
<td>733</td>
</tr>
<tr>
<td>10</td>
<td>31</td>
<td>29</td>
<td>775</td>
</tr>
<tr>
<td>11</td>
<td>28</td>
<td>29</td>
<td>467</td>
</tr>
<tr>
<td>12</td>
<td>36</td>
<td>30</td>
<td>800</td>
</tr>
<tr>
<td>13</td>
<td>47</td>
<td>29</td>
<td>783</td>
</tr>
<tr>
<td>14</td>
<td>33</td>
<td>24</td>
<td>733</td>
</tr>
<tr>
<td>15</td>
<td>46</td>
<td>30</td>
<td>767</td>
</tr>
<tr>
<td>16</td>
<td>35</td>
<td>32</td>
<td>467</td>
</tr>
<tr>
<td>Mean</td>
<td>31</td>
<td>28</td>
<td>630</td>
</tr>
<tr>
<td>Standard deviation (SD)</td>
<td></td>
<td>4.5</td>
<td></td>
</tr>
</tbody>
</table>

4.2.1.2 Sample tree selection

Sap flow sensors were installed on trees across the tree size class based on dbh determined through a vegetation survey. It is highly recommended that the selection of sample trees in a mixed stand needs to follow random stratified sampling across the tree size class to reduce the error in scaled stand transpiration (Granier et al., 1990; Hatton et al., 1995; Nadezhdina et al., 2002). A study by Hatton et al. (1995) on Eucalyptus populnea found that stratified sample selection of six trees in three size classes based on tree dbh had a coefficient of variation < 5% and similarly for three sample trees, the coefficient of variation was < 12%. It is well documented that dominant trees forming one-third of stand
population account for about two-thirds of the total stand transpiration (Kelliher et al., 1992; Vertessy et al., 1997; Nadezhdina et al., 2002) and therefore it is important to sample more trees in higher size classes. Another sample tree selection based on ‘quantiles of total’ statistical technique was suggested by Nadezhdina et al. (2002). In this technique all trees in the stand are sorted according to the selected biometric parameter in ascending order and divided into equal portions based on number of samples required.

Tree size distribution in the stand was determined and accordingly the best possible random stratified allocation of HPV sensor for each tree class was made within the available resources (Table 4.2 and Figure 4.4). A total of 9 sample trees across the tree class based on dbh were selected for sap flow measurement. Three trees were sampled in the tree class size of 25-32 cm, which had the highest number of trees of 156, whereas two trees in each tree class of 15-25 cm and 35-45 cm were sampled, with 139 and 92 trees respectively. Trees selected were free from damage due to fire, pruning, cracks or major knots and feasible to work in terms of accessibility. The numbers of trees between the dbh 55 to 65 cm were 11. It was not possible to instrument trees in this class (bigger than 50 cm dbh) as the thermistor length of the instrument used could not reach deeper layers of the sapwood for sap flow measurement. As the number of trees in this class was 11 (2%), it was not a significant loss in sampling of trees for sap flow.

The sap flow velocity for the 9 sample trees was recorded every 30 minutes for a period of 14 months from 4th February 2008 to 3rd May 2009. The annual transpiration results were worked for the first 12 months (4th February 2008 to 3rd February 2009) and presented in Chapter 5 (water use by crack willows in the wetland). A further three months data collected were used for estimating evapotranspiration of the wetland for water balance conducted for the dry period of 2008 and 2009, presented in Chapter 6 (wetland water balance and groundwater flux). The sap flow data gap for the month of November 2007 to January 2008 for the wetland water balance study was estimated based a regression model with PET measured for grassland, which was 4 km away from the study site. The details of the regression relationship are provided in Chapter 5.
Table 4.2 Frequency table of tree distribution and samples trees selected for installation of HPV sensors

<table>
<thead>
<tr>
<th>Tree class (dbh in cm)</th>
<th>Number of trees</th>
<th>% trees</th>
<th>Sample trees with HPV sensors</th>
<th>dbh of sample trees with HPV sensors</th>
</tr>
</thead>
<tbody>
<tr>
<td>5-15</td>
<td>64</td>
<td>13</td>
<td>1</td>
<td>14</td>
</tr>
<tr>
<td>15-25</td>
<td>139</td>
<td>28</td>
<td>2</td>
<td>20, 25</td>
</tr>
<tr>
<td>25-35</td>
<td>156</td>
<td>32</td>
<td>3</td>
<td>27, 29, 35</td>
</tr>
<tr>
<td>35-45</td>
<td>92</td>
<td>19</td>
<td>2</td>
<td>39, 40</td>
</tr>
<tr>
<td>45-55</td>
<td>26</td>
<td>5</td>
<td>1</td>
<td>50</td>
</tr>
<tr>
<td>55-65</td>
<td>11</td>
<td>2</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>488</strong></td>
<td><strong>100</strong></td>
<td><strong>9</strong></td>
<td><strong>9</strong></td>
</tr>
</tbody>
</table>

**Figure 4.4 Sample tree distribution across the tree class interval**

Note: the values on each bar are the number of trees sampled for sap flow measurement

**4.2.1.3 Integration of sap flow from point measurements**

Sap flow velocities are single point measurements in the conducting wood area and based on this information sap flow volume of the tree is estimated. In the present study it was decided to have four point measurements at set incremental depths from near the cambium...
to near the heartwood. Hatton et al. (1995) and Vertessy et al. (1997) found stratified placement of sensors with four point measurements around the tree would provide reliable estimate of sap flow velocity and this was followed by Schaeffer et al. (2000) in their study on Salix goodingii in San Pedro River, USA, and Doody et al. (2006) for Salix babylonica in the riparian region of southern New South Wales of Australia. Also, the review paper on the studies of estimating sap flow using HPV instruments by Smith and Allen (1996) showed that more than four sensors per tree would provide best estimates of sap flow.

The total sapwood area on the sample trees was divided into four equal areas and each received a sensor in a stratified manner, which was implanted randomly on north, south, east and west aspects of the stem at breast height (Figure 4.5). This approach was adopted based on the radial sap flow variability experiment (to be discussed later) and earlier studies on Salix species. It was standardized for all sample trees to have sensors at stratified depths of 20, 40, 60 and 80% of sapwood from the outer periphery (under the bark) (Figure 4.5). These point estimates of sap velocities were integrated into sap flow volume by weighting the measurement for individual sensor by the proportion of conducting wood area they sampled.

Sap flow of tree \( Q = \sum \text{sap flow of each section (v)} \times \text{sap wood area of each section (A)} \)
Figure 4.5 Diagram of HPV sensors installed in a stratified manner at four incremental depths (north, south, east and west aspects of the stem) at breast height

4.2.1.4 Errors in point estimates of sap flow

The potential sources of errors with point estimation are measurement of wound diameter and volumetric wood and water contents.

4.2.1.4.1 Wound analysis

The heat pulse method requires the drilling of access holes (2 mm wide) for the thermistors and the heater, causing substantial mechanical damage, disturbing the sap flow velocity. In addition to the interruption of flow pathways by the insertion of the probes, intact vessels may become occluded as the plant responds to wounding by forming tylosis and therefore not able to carry water (Butterfield and Meylan, 1980; Barrett et al., 1995). This results in an area of non-conducting tissue directly surrounding the probe.

In general, wound diameters are tedious to estimate and can be variable among tree species. The commonly used methods to estimate the wound diameter is core extraction from the tree containing the drilled holes used for thermistor implantation. The wound diameter in the extracted core is indicated by the presence of tylosis bud initiation around
the drilled holes and examined under binocular light microscope or scanning electron microscopy (Olbrich, 1991; Dunn and Connor, 1993; Barrett et al., 1995; Benyon, 1999). The other method is adding dye to the water absorbed by a cut tree and then cutting the stem exactly where the holes are drilled. The stem cross section examined for staining sapwood method would show no stain around the area of drilled holes where the flow of water is interrupted and can be measured to indicate the wound extent (Olbrich, 1991; Anon, 1996). The sensitivity and error analysis by Olbrich (1991), Hatton et al. (1995), Anon (1996) and Green et al. (2003) showed that wound diameter estimation is among the most highly sensitive parameters, where sap flow estimation error could be more than 50% if not measured accurately.

The heat pulse technique would be far less useful without some corrections for distortion of wounds and if ignored, sap flow will be underestimated. The wounds rupture the capillarity in the local region around the probes and therefore the heat originating at the heater must move solely by diffusion through this dead zone before it can ascend due to convection. Wound correction coefficients applicable to a range of wound sizes have been generated using numerical models which allow accurate corrections to be made. Swanson and Whitefield (1981) were first to use finite-difference numerical solutions for convection and diffusion equations for idealized wood with varying wound diameters. The results of these corrections were summarized in polynomial equations related to wound diameter. Exact themistor spacings together with corrections of Swanson and Whitefield (1981) has enabled accurate application of the heat pulse technique in the absence of calibration. Later these simulations were repeated by Commonwealth Scientific and Industrial Research Organisation (CSIRO) Division of Water Resources with improved numerical solutions and for materials specific to the Greenspan Sap flow Sensor and incorporated in the commercial product (Anon, 1996). The correction form equation is as follows.

\[ V_c = a + bV_h + cV_h^2 \]

Where \( V_c \) is the corrected heat pulse velocity and \( a, b, \) and \( c \) are wound diameter-specific coefficients.
In the present study the stem cross section of cut tree experiment was taken exactly at the drilled holes of sensor implantation. It was examined for staining of sapwood around the area of drilled holes, and the area not stained was considered as the wound extent. The wound diameter measured on the cut stem after the cut tree experiment was around 2.1 mm. The correction for the wound width was incorporated into the estimation of sap flow velocity as per the manual of HPV technique.

The deposition of resin in the sapwood around the wound would generally increases the wound extent over the period of the experiment (Smith and Allen, 1996). However crack willow sapwood does not contain any resin and chances of wound reactions would be minimal. However to avoid the error in sap flow velocity due to increase in wound extent over the study period the HPV sensors were moved to newly drilled holes on the stem every three months as per the suggestion of Olbrich (1991) and Smith and Allen (1996).

4.2.1.4.2 Determination of volumetric wood and water contents

Error in estimation of volumetric wood and water contents is low and not highly sensitive to errors in the estimation of sap flow (Olbrich, 1991; Hatton et al., 1995; Anon, 1996). There are many studies which show a decrease in the volumetric fraction of water in sapwood sample as available soil moisture decreases for the growing tree (Telewski and Lynch, 1991; Anon, 1996; Borghetti et al., 1998). To overcome this problem it is advisable to estimate the volumetric wood and water contents of the tree during different season of the study. The methodology for volumetric wood and water contents can be found in studies of sap flow by Edwards and Warwick (1984), Anon (1996) and Smith and Allen (1996).

For the present study the estimation of volumetric wood and water contents of the wood for sample trees was determined gravimetrically from wood core samples collected for sapwood area estimation. The wood cores immediately after estimation of sapwood area were rolled up in a plastic wrap and kept in airtight containers. Later in the lab, weight of the cores was determined using electronic balance. Fresh weight was recorded and the samples were then immersed in water, and the weight of displaced water was recorded as volume of wood core. The wood core was then oven dried at 70° C for 48 hours and the dry weight recorded. To confirm that wood was dried, it was again kept in the oven for
another 24 hours and weighed to see if there was any further decrease in the weight of the wood core.

\[
\text{Volume fraction of water} = \frac{\text{Fresh weight} - \text{Dry weight}}{\text{Immersed weight}}
\]

\[
\text{Volume fraction of wood} = \frac{\text{Dry weight}}{1.53 \times \text{Immersed weight}}
\]

The specify gravity of wood is nearly constant at 1530 kg per cubic meter and therefore factored as 1.53.

The trees in the study area were in a wetland and had sufficient soil moisture all around the study period including summer, and the difference in the wood water contents would be nil. Therefore volumetric wood and water contents were measured only once during the study period.

4.2.1.5 Errors in flow estimation for single tree

The errors associated with sap flow estimation for a single tree are radial variability in sap flow density and determination of conducting wood area, which can be uncovered by various methods. The methods used in understanding the errors associated with integration of flow for a tree are described in detail by Hatton et al. (1990), Cermak et al. (1992), Hatton et al. (1995) and Nadezhdina et al. (2002).

4.2.1.5.1 Determination of radial sap flow variability across the conducting wood area

Sap flow instruments measure sap flow velocity at a single point in the conducting wood area, and based on this information sap flow volume of the tree was estimated. However there are a large number of studies showing large variability of sap flow velocity within the conducting wood area. Therefore, to provide an accurate estimate of sap flow, one has to understand the radial sap flow variability across the conducting wood area.
The largest source of sap flow variation is higher within asymmetric tree stems and close to uniform in symmetric trees (Vertessy et al., 1997). Therefore it is suggested to select symmetrical stems for implantation of sap flow instruments and sample as many trees as possible of different size (Granier et al., 1996; Vertessy et al., 1997). In contrast, Nadezhdina et al. (2002) found that variation in sap flow is high within trees (coniferous and broadleaf tree species) and comparatively low between trees, and therefore suggested the need to have more spatial point sampling of sap flow velocity within the tree. There are many such studies with contrary results. But most studies suggested determining the radial sap flow pattern and deciding the required precise sampling requirements as this would differ between species, growing conditions and age of the stand (Dye et al., 1991; Olbrich, 1991; Hatton et al., 1995; Smith and Allen, 1996; Vertessy et al., 1997; Nadezhdina et al., 2002). This would reduce the error in sap flow estimation within the tree stem to a great extent.

The number of point measurements of sap flow velocity varies widely in earlier studies. Hatton et al. (1995) found stratified placement of probes with four point measurements would provide sap flow velocity results with < 15% error and could be reduced with the increase in number of sensors per tree of Eucalyptus populnea. Similarly, Doody et al. (2006) used four sensors to estimate the sap flow of Salix babylonica in a riparian region of southern New South Wales. Schaeffer et al. (2000) used three to five point measurements based on tree size on Salix goodingii and cottonwood in the San Pedro River area, USA. Based on the review of sap flow estimated using HPV instruments, Smith and Allen (1996) suggested four or more sensors per tree would provide best estimates of sap flow at different depths supported with experiment on radial variation in sap flow velocity. It was generally understood that four sensors per tree would provide information on sap flow rates with a low level of error, and also help in the efficient utilisation of the resources.

It is important to implant the thermistors at set depths from near the cambium to near the heartwood. It is always advisable to implant all around the tree at equal distance, and if using four thermistors, they should be implanted at 90° to one another. Later these point estimates of sap velocities need to be integrated into sap flow. The easiest way is to take an average velocity and multiply by the conducting wood area. Alternatively, each
thermistor could be weighted by the area of conducting wood area and use the algorithm of Hatton et al. (1990), which has a low error arising from the measurement errors or random variation of sap flow velocity, when compared with fitting a polynomial to the velocity profile approach developed by Edward and Warwick (1984).

A commonly used method in understanding the radial sap flow variability and sapwood boundaries is to insert sensors at different depths, and estimate sap flow velocity in different regions of the sapwood. Another method is to insert the thermistors at 2 mm increments of depth on a day of relatively maximum transpiration. An innovative method of special visualization procedures viz., radial patterns, 3D visualization and network and 2D colour visualization is provided by Cermak et al. (2004) for understanding the radial variation of sap flow velocity.

The earlier studies showed that radial sap flow variability is important to decide the optimum number of sampling points and their distribution pattern required within the sapwood to reduce the error in estimation of sap flow velocity. Therefore, in the present study to estimate the spatial variability in sap flow across the conducting wood area, 8 sensors were implanted at every 5 mm for a tree with a 45 mm radius of sapwood. The sap flow velocity was recorded for 10 days (1\textsuperscript{st} to 10\textsuperscript{th} January 2008) at 30 minutes intervals. The measured sap flow of each thermistor was weighted by the corresponding area of conducting wood area and summed for total sap flow of the sample tree.

The results of the experiment showed the sap flow velocity increased dramatically in newly formed sapwood and then reduced further towards the heartwood. The average velocity of sap flow for different depths is presented in Table 4.3 and Figure 4.6. Given this linear pattern in the variation of radial sap flow velocity, the sapwood was divided equally and each represented with a sensor at incremental depths of 20, 40, 60 and 80% of sapwood area for the present study.
Table 4.3 Radial variation of sap flow across the conducting wood area

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Sensor depth of implantation (mm)</th>
<th>Average sap flow velocity (l/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5</td>
<td>18.6</td>
</tr>
<tr>
<td>2</td>
<td>10</td>
<td>19.9</td>
</tr>
<tr>
<td>3</td>
<td>15</td>
<td>17.5</td>
</tr>
<tr>
<td>4</td>
<td>20</td>
<td>14.0</td>
</tr>
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<td>5</td>
<td>25</td>
<td>11.8</td>
</tr>
<tr>
<td>6</td>
<td>30</td>
<td>9.3</td>
</tr>
<tr>
<td>7</td>
<td>35</td>
<td>6.1</td>
</tr>
<tr>
<td>8</td>
<td>40</td>
<td>1.9</td>
</tr>
</tbody>
</table>

Figure 4.6 Radial variation of sap flow velocity across the conducting wood area (sap wood)
The spatial correlation of coefficient matrix relating the sap flow velocity measured by each sensor (total 8 sensors) at 5 mm incremental depth is presented in Table 4.4. This shows the strength and direction of the linear association between two sensors independently. The range of ‘r’ values for the sap flow velocity at different depths recorded every 30 minutes ranged from 0.52 to 0.97 (Table 4.4) at the 0.05% confidence level, with an average value around 0.79. This shows that, on average, the sensors placed throughout the sapwood varied uniformly through the sapwood area. However a closer look at the matrix shows the velocity to be more uniform in the outer sapwood with most of the r values above 0.80 compared with the inner sapwood which was below 0.70.

Table 4.4 Correlation matrix of sap flow velocity at incremental depths of 5 mm across the conducting wood area

<table>
<thead>
<tr>
<th>Depth (mm)</th>
<th>5</th>
<th>10</th>
<th>15</th>
<th>20</th>
<th>25</th>
<th>30</th>
<th>35</th>
<th>40</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>1.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>0.86</td>
<td>1.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>0.87</td>
<td>0.99</td>
<td>1.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>0.85</td>
<td>0.96</td>
<td>0.97</td>
<td>1.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>25</td>
<td>0.75</td>
<td>0.71</td>
<td>0.72</td>
<td>0.70</td>
<td>1.00</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>0.70</td>
<td>0.67</td>
<td>0.67</td>
<td>0.65</td>
<td>0.67</td>
<td>1.00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>35</td>
<td>0.62</td>
<td>0.61</td>
<td>0.61</td>
<td>0.59</td>
<td>0.53</td>
<td>0.55</td>
<td>1.00</td>
<td></td>
</tr>
<tr>
<td>40</td>
<td>0.68</td>
<td>0.80</td>
<td>0.79</td>
<td>0.78</td>
<td>0.60</td>
<td>0.55</td>
<td>0.52</td>
<td>1.00</td>
</tr>
</tbody>
</table>

*Figures in bold show the minimum and maximum values of r

4.2.1.5.2 Determination of conducting sapwood area boundary

It is understood that in many tree species the colour change associated with the heartwood boundary may not be exactly coincident with the conducting wood boundary (Hatton et al., 1995; Smith and Allen, 1996). Therefore, it is important to determine the true sapwood boundaries supporting sap flow of the crack willow trees.

The change in colour between the sapwood and the heartwood was quite clear in crack willows and it was easy to determine the conducting wood boundary. To confirm this the experimental tree for determination of radial sap flow variability was used. On a normal
sunny day in the summer (11th January 2008) during midday HPV sensors on the experimental tree were moved 2 mm inward from the deepest measuring point which was at 93% (42 mm) depth and sap flow velocity recorded. The sensor was relocated a further 2 mm deeper and the procedure repeated until the flow recorded zero.

The experiment results showed that sap flow velocity was close to zero at 98% depth of sapwood, and no sap flow in the heartwood (Table 4.5). This clearly shows no sap flow beyond the visible sapwood area. However one needs to be aware that HPV instruments are not good at recording low sap flow velocities. Therefore it was re-confirmed through the cut tree experiment in which sapwood was stained to a depth of around 97%. In other words the stained area was less than 2 mm away from the heartwood boundary determined through change in colour between the sapwood.

<table>
<thead>
<tr>
<th>Sapwood depth (mm)</th>
<th>% depth</th>
<th>Sap flow velocity (l/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>40</td>
<td>89</td>
<td>1.9</td>
</tr>
<tr>
<td>42</td>
<td>93</td>
<td>0.6</td>
</tr>
<tr>
<td>44</td>
<td>98</td>
<td>0.0</td>
</tr>
<tr>
<td>46</td>
<td>102*</td>
<td>0.0</td>
</tr>
</tbody>
</table>

* This measurement was in the heartwood

Based on the results of the above experiments, the conducting sapwood area of the sample trees was determined by extracting wood cores using a Pressler borer. Four samples were taken equidistantly around the bole, close to the thermistor implantation location for all the sample trees. The sapwood area used was 97% to upscale the sap flow from point measurements to tree, as no sap flow was detected closer towards the heartwood.

4.2.1.5.3 Determination of low sap flow velocity

Recording zero flows and low flow rates below a minimum threshold with the HPV technique is prone to errors. Barrett et al. (1995) and Becker (1998) found that low flows were not recorded by the HPV method in *Eucalyptus maculate* and *Dryobalanops aromatica* because of the low sensitivity of the thermistor to small changes in sapwood
temperature under these circumstances. Low flow usual occurs in the early morning and late evening, and zero flow during midnight but records over these times are important for the accurate estimation of daily transpiration of the stand. Swanson and Whitefield (1981) showed how numerical solutions could be used to reduce errors in the measurement of heat pulse velocity occurrence at sap velocities below 3 cm/hour. Similarly, there are several conservative statistical estimates of minimum detectable sap flow suggested until the instrument is improved. Becker (1998) suggested considering the median of the night time sap flow during a specified short period as a threshold for zero flow. It was also recommended that sap flow rates be first smoothed to avoid distortion by extreme values. In some studies threshold minimum values were determined based on net radiation and VPD values of the day and assumed that there is energy for sap flow to occur (Cermak et al., 1984). However, in temperate forests it would not be worthwhile to use this approach because of dew on the leaves, water stored in the trunk/branches/leaves, and rain which will delay the start of transpiration (time lag) in the day, even though there is an increase in net radiation and vapour pressure deficit (VPD). In the same study, Cermak et al. (1984) also suggested looking at average re-occurrence with confident limits to determine night time threshold minimum values. Benyon (1999) determined the threshold sap flow values based on data collected between 0000 and 0500 hours for nights when relative humidity was close to 100% for well watered four year old plantation of Eucalyptus grandis in Australia. The mean and standard deviation of sap flow velocity for several such nights was computed for each thermistor and upper 1% confidence limit taken as the threshold or zero value. However if one uses the recently developed instrument ‘heat-ratio method’ by Burgess et al. (2001), it is possible to record the low flows with very low or no error, which is an improved version over the compensation HPV technique.

In the present study, for accurate estimation of total sap flow it was important to determine a threshold level for low flow values below which no flow is assumed. The method suggested by Benyon (1999) was used to determine the threshold sap flow velocity value. With low VPD and no energy to support transpiration, there would be no sap flow or very low sap flow on days with relative humidity close to 100% between 0000 and 0500 hours. The mean and standard deviation of sap flow velocity for several such nights (> 15 nights) was computed for each thermistor and upper the 1% confidence limit taken as the threshold value.
4.2.1.5.4 Sapwood properties

There are two types of water-conducting elements in the xylem known as tracheids and vessels. Tracheids are spindle-shaped cells up to 5 mm long and 30 micrometer in diameter, while vessels which are tube-like structures ranging from a few centimetres to many meters in length and 20 to 700 micrometer in diameter. Angiosperm (hardwood) xylem contains both vessels and tracheids, but gymnosperm (softwood) xylem contains only tracheids. Movement of water from one xylem element to another is facilitated by pits or thin places in their walls (Zimmermann, 1983). This wood anatomy of hardwood and softwood has very large implications for the calibration requirements of the heat pulse velocity method to estimate sap flow. For tree species with thermally homogeneous sapwood, sap flow can be estimated without error. This is possible because the interstitial distances between the elements is low and therefore the time required for thermal equilibrium between sap and wood matrix is negligible. Swanson (1983) (cited in Smith and Allen, 1996) concluded that interstitial distances of more than 0.4 mm are sufficient to cause thermal inhomogeneities. This means the technique works well in softwood species and in ring porous and diffuse porous hardwoods with closely spaced xylem vessels of less than 0.4 mm (Green and Clothier, 1988; Swanson, 1994). However, in other hardwoods it may be necessary to conduct empirical calibrations to measure sap flow using the HPV technique (Smith and Allen, 1996; Green et al., 2003).

Crack willow consists of diffuse porous wood and the xylem vessels are closely spaced with interstitial distances less than 0.4 mm, making them thermally inhomogeneous (Cermak et al., 1984). Therefore there was no requirement for calibration of the HPV technique.

4.2.1.6 Errors in flow estimation for a stand

Sap flow volume of individual trees needs to be converted to estimates of transpiration per unit of land area to be used in hydrological studies and in most cases expressed in mm per day. The best approach to such scaling problems is to measure flow of all the trees in the study area, but it is unusual to have sufficient instruments available (Kelliher et al., 1992; Kostner et al., 1992). Therefore various scaling parameters are used to scale tree water use of sample trees to the stand level.
4.2.1.6.1 Scaling sap flow from sample trees to a stand

Scaling tree water use from sample trees to the stand is done using various scaling parameters viz., ground area covered by trees, leaf area of tree, conducting wood area at 1.3 m height from the ground, dbh, other tree biometric parameters, remote sensing images and hydrologic models. Detailed reviews of scaling methods are provided by Hatton et al. (1995), Hatton and Wu (1995), Anon (1996), Smith and Allen (1996), Vertessy et al. (1997) and Cermak et al. (2004). With tree plantations having uniformity with size, age, spacing and closed canopy, it is easy and simple to extrapolate the sap flow from sampled trees to stand. However in natural forests with different tree size, spacing and especially those forming a hierarchy, scaling needs to be applied with caution. In mixed stands where spatial and temporal variation in transpiration is high because of access to resources and especially for light, scaling can be done based on the theory developed by Hatton and Wu (1995) or make sub groups of tree classes with similar size and follow the integration technique (Granier et al., 1990; Dunn and Connor, 1993). Also the error of scaling is dependent on intensity and method of sample trees selected for sap flow measurement.

There have been various attempts to scale transpiration using some measure of ground area. Hatton and Vertessy (1990) used the area of domain exploited by each tree (tessellation method). In this approach, the domain exploited by each tree (Pinus radiata) is defined from midway between the stem of the tree in question and its nearest neighbours, thus forming a tessellation around each tree. They found a correspondence between scaling estimations and meteorological methods (Bowen Ratio), but sap flow scaling overestimated the transpiration. Walker et al. (1989) proposed the Ecological Field Theory (EFT), which could be adopted for scaling water use of sample trees. Hatton et al. (1995) compared both the tessellation method and EFT and found stronger correlation of estimated sap flow with EFT.

Among the tree biometric parameters most widely used was tree dbh for scaling of water use at the stand level. The different scalars (biometric parameters) were compared by Diawara et al. (1991), Hatton et al. (1995), Anon (1996), Vertessy et al. (1997), Cermak et al. (2004) and Eamus et al. (2006). They found dbh to provide stronger correlations
and to be more robust. There are many studies showing the strong relationship between the dbh and sapwood area and therefore usage of dbh for scaling was largely accepted (Vertessy et al., 1997; Schaeffer et al., 2000; Eamus et al., 2006). The scaling based on sapwood area at breast height (1.3 m) and leaf area is highly laborious but also error prone as it is difficult to estimate sapwood area and leaf area accurately (Hatton et al., 1995; Vertessy et al., 1997). However, leaf area is one among the most widely used scalars to estimate the stand transpiration in most of the short duration studies as they are cost effective and quick methods to estimate leaf area. Successful use of leaf area for scaling and its advantages are well documented in studies by Cermak (1989), Allen and Grime (1995), Sprugel et al. (1996) and Cermak (1998). However the season of the study period is very important because the leaf area variation across the season is very high in most of the tree species and affects the scaling of sap flow (Thorburn et al., 1993; Eamus et al., 2006) and it is not advisable to be used in long term studies. Leaf area of a tree and stand can be estimated using different methods as described by Larsen and Kershaw (1990), Fassnacht et al. (1994) and Breda (2003).

Other scaling methods available are remote sensing techniques and hydrologic models used recently, and seem promising for large scale studies but all need to be developed for more accurate results. Advantages of remote sensing and hydrologic models is that they covers large spatial and temporal changes and adequately describe the daily and even hourly transpiration at larger units under varying environmental conditions (Meiresonane et al., 1999; Chiesi et al., 2002; Anselmi et al., 2004; Cermak et al., 2004; Chiesi et al., 2007).

For the present study dbh was used to scale the measured sap flow rate on the sample trees to the stand level, which is suggested as the best tree biometric parameter for stand level scaling (Anon, 1996; Vertessy et al., 1997; Schaeffer et al., 2000; Cermak et al., 2004; Eamus et al., 2006). The tree class intervals based on dbh were prepared through a vegetation survey. A non-linear relationship of the form y=ax^b was computed between dbh of sample trees (x) and daily sap flow rate (y) to understand the sap flow rate across the tree class and was used for the scaling.
The sap flow rate used for each diameter class was the average daily sap flow of all sample trees in each diameter class for the entire study period. The $r^2$ value of 0.97 represents a strong relationship between the tree size (dbh) and sap flow rate (Figure 4.7). This shows that the tree biometric parameter dbh could be used for scaling the tree water use from the sample trees to the stand. The curvilinear relationship showed that, as the size of the trees increases the sap flow increases exponentially. It is understood that two thirds of sap flow in the stand is through one third of the dominant class vegetation (Vertessy et al., 1997; Nadezhdina et al., 2002). This was largely true in the present study with the sap flow of a sample tree with a dbh 50 cm being twice the sap flow of a 42 cm dbh tree. The results of the regression relationship were used to upscale the sap flow rate to daily tree sap flow estimated for the whole wetland area (stand level) and presented in mm per day.

The scaling of sap flow through relationship developed without the sample tree 50 cm (considering it as outlier) and product of sap flow rate with sapwood area of stand was not much different curvilinear relationship in the Figure 4.7. With this it was decided to use all the sample trees in scaling of sap flow to the stand and therefore the curvilinear relationship in figure 4.7 was used.

![Graph showing the relationship between DBH and Sap flow rate](image)

**Figure 4.7 Non-linear regression relationship between tree size dbh and average daily sap flow rate**
4.2.1.7 Validation of HPV technique

To assess the accuracy given the uncertainties in the HPV technique it is important to validate the method against a known sap flow rate. Two approaches viz., mass and volumetric methods of validation were described by Green and Clothier (1988). The laboratory method (mass) is to obtain known tree water use using an electronic balance to compare with estimated sap flow using the HPV technique (Barrett et al., 1995). This could be undertaken only if there is access to a tree of manageable size growing in a pot and therefore has been rarely used. The other method commonly used is a cut tree experiment, which is based on the volumetric measurement of usage of water under field conditions as described by Robert (1977) (cited in Olbrich, 1991) and also the one used in the present study. A modified technique of cut tree experiment was used for large size trees by Olbrich (1991) and Vertessy et al. (1997). There are also a few studies that try to understand the accuracy and sensitivity of the HPV technique using a non-biological system (Anon, 1996; Becker, 1997). However, these methods are expensive and therefore were not followed. However, it is important to recognize that sap flow recorded on cut trees is subject to error because of changes in water absorption by xylem tissues, with some vessels and tracheids getting blocked due to the cut. Cut experiments can only be used for an approximate evaluation of the HPV technique of sap flow estimation (Cermak et al., 1992) and are not a 100% fool-proof method of validation.

There are various ways the cut tree experiment can be undertaken, based on the size of the tree, resources available and length of experiment (Green and Clothier, 1988; Olbrich, 1991; Cermak et al., 1992; Dunn and Connor, 1993; Vertessy et al., 1997). In this study the experiment was conducted under clear skies supporting maximum transpiration on a small tree of manageable size (12 cm dbh sapling) with a very small crown, from 29th and 30th November 2009, and procedures followed as per the manual. The thermistors of the HPV were installed on the tree which was then cut quickly at the base and placed immediately in the measuring container of water. Then it was quickly recut at an angle under water about 25-30 cm above the first cut to avoid the formation of embolisms in the xylem that would restrict water flow and entry of additional air. Evaporation of the water from the container was prevented by shading and adding a thin film of oil to the water surface. Additional care was taken to prevent oil contaminating the cut surface of the tree. The water absorbed by the tree for transpiration was replaced every 60 minutes (between
07.00-20.00 hours) to the initial reference level, and compared with the sap flow data recorded through the HPV technique.

Sap flow measured on the cut tree was underestimated by 7%, when compared to evaporation of water from the container (Table. 4.6). The sap flow measured during the experimental period was 1.13 l/hr and evaporation from the container was 1.21 l/hr. This difference could be due to the cutting of the tree, with some vessels and tracheids getting blocked, and open water evaporation from the measuring container. It could be also due to various experimental errors and little to do with the HPV technique. However one needs to remember that cut tree experiments can only be used for an approximate evaluation of the HPV technique of sap flow estimation (Cermak et al., 1992) and is not a 100% fool-proof method of validation.

Table 4.6 The hourly sap flow rate and evaporation of water from the measuring container of the cut tree experiment

<table>
<thead>
<tr>
<th>Date/Time</th>
<th>29&lt;sup&gt;th&lt;/sup&gt; Nov 2008</th>
<th>30&lt;sup&gt;th&lt;/sup&gt; Nov 2008</th>
<th>Average for both days</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Evaporation l/hr</td>
<td>Sap flow l/hr</td>
<td>Evaporation l/hr</td>
</tr>
<tr>
<td>07:00:00</td>
<td>0.44</td>
<td>0.38</td>
<td>0.51</td>
</tr>
<tr>
<td>08:00:00</td>
<td>0.72</td>
<td>0.66</td>
<td>0.88</td>
</tr>
<tr>
<td>09:00:00</td>
<td>1.27</td>
<td>1.06</td>
<td>0.96</td>
</tr>
<tr>
<td>10:00:00</td>
<td>1.34</td>
<td>1.37</td>
<td>1.26</td>
</tr>
<tr>
<td>11:00:00</td>
<td>1.47</td>
<td>1.32</td>
<td>1.40</td>
</tr>
<tr>
<td>12:00:00</td>
<td>1.56</td>
<td>1.39</td>
<td>1.58</td>
</tr>
<tr>
<td>13:00:00</td>
<td>1.57</td>
<td>1.60</td>
<td>1.72</td>
</tr>
<tr>
<td>14:00:00</td>
<td>1.56</td>
<td>1.60</td>
<td>1.67</td>
</tr>
<tr>
<td>15:00:00</td>
<td>1.50</td>
<td>1.48</td>
<td>1.60</td>
</tr>
<tr>
<td>16:00:00</td>
<td>1.58</td>
<td>1.41</td>
<td>1.48</td>
</tr>
<tr>
<td>17:00:00</td>
<td>1.29</td>
<td>1.11</td>
<td>1.25</td>
</tr>
<tr>
<td>18:00:00</td>
<td>1.18</td>
<td>1.04</td>
<td>1.20</td>
</tr>
<tr>
<td>19:00:00</td>
<td>0.93</td>
<td>0.81</td>
<td>0.97</td>
</tr>
<tr>
<td>20:00:00</td>
<td>0.52</td>
<td>0.39</td>
<td>0.62</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>16.93</strong></td>
<td><strong>15.62</strong></td>
<td><strong>17.09</strong></td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td><strong>1.21</strong></td>
<td><strong>1.12</strong></td>
<td><strong>1.22</strong></td>
</tr>
</tbody>
</table>
The linear regression relationship between the evaporation of water from the container and measured sap flow \( (r^2 = 0.97) \), represents a strong positive relationship (Figure 4.8). This shows that the sap flow measured using the HPV technique is largely reliable and could be used for the estimation of transpiration of the crack willows in the present study.

![Figure 4.8 Linear regression relationship between tree size evaporation (x) and sap flow rate (y)](image)

Cut tree experiments can also used for estimation of wound diameter, conducting sapwood area and determining the variability of radial sap flow velocity (see sections 4.2.1.4.1 and 4.2.1.5.2). At noon on the last experimental day stain (Eosin) was added to the water absorbed by the cut tree. After one hour the tree was cut 30 cm above the implanted sensors and the stem removed from the container. Later the stem was cut exactly at the drilling points and examined for the extent of staining in the xylem tissue, which was considered as the sap conducting area. On the same stem cross section the drilling points were examined for the non-stained area (flow of water is interrupted), which was considered as the wound extent area (Cermak et al., 1984; Olbrich, 1991; Cermak et al., 1992; Dunn and Connor, 1993; Barrett et al., 1995; Hatton et al., 1995; Anon, 1996; Zziwa, 2003).
4.2.1.8 Validation of the estimated transpiration

The validation described above was for the HPV sap flow technique used for estimation of the sap flow rate on a single tree through the cut-tree experiments. Similarly, it is important to validate the scaled sap flow rates to the stand level, presented as transpiration rates for the wetland. Validation of scaling methods is usually done through micrometeorological methods such as the Bowen ratio or eddy correlation method (Granier et al., 1990; Hatton and Vertessy, 1990; Diawara et al., 1991) but these have limitations. They are not usually followed in most of the studies because they are laborious, expensive and require substantial experimental effort. Secondly there could be errors involved in estimation of transpiration using micrometeorological methods which may be difficult to identify. The requirement of this validation depends on the accuracy of the estimated stand transpiration in the study. In the present study the validation of estimated transpiration was not followed due to the practical limitations of the validation methods.

4.2.1.9 Transpiration in relation to VPD

VPD is one among a few meteorological parameters supporting transpiration and forming strong relationships (Cermak et al., 1984; Kelliher et al., 1992; Herzog et al., 1998; Wullscheleger et al., 1998; Oren et al., 1999; Lambs and Muller, 2002). Therefore it was estimated to understand the relationship with the measured transpiration of crack willows in the present study.

VPD was estimated using the equation from Allen et al. (2000), which is based on daily maximum and minimum temperatures and relative humidity data. The required data for estimation of VPD were taken from TDC weather station. The hourly data for accurate estimation of VPD was not available from the weather station. Therefore the estimation of VPD was not accurate and may not show strong correlation with evapotranspiration estimation.

4.2.1.10 Effect of leaf phenology on transpiration

Leaf phenology plays a major role in the determination of transpiration rates along with meteorological parameters (Kelliher et al., 1992; Schaeffer et al., 2000; Lambs and
Muller, 2002; Doody et al., 2006; Eamus et al., 2006). It is apparent from earlier studies that the transpiration rate would be greatly affected by phenology of trees due to their deciduous nature especially during autumn and spring. To have a rough understanding of leaf cover, the monthly dry weight of leaves dropped on a pan (1.21 m diameter) was recorded. The leaves were collected on a monthly basis, oven dried and weighed. By the first week of May the trees were devoid of leaves, and fresh leaves after the dormant season again started dropping from the second week of September. Therefore there was no leaf fall data collected from May to August.

Similarly, the leaf cover percent of the willow stand was established based on visual observation during regularly field visits. The bench mark leaf cover for the wetland was considered with mid-winter leaf cover as 0% (May to August) and mid-summer as 100% leaf cover (December and January). Based on the established bench mark leaf cover the monthly leaf cover percent was established through visual observation during regular field visits for the duration of the study period.

4.2.1.11 Understorey transpiration

The understorey cover under the crack willow stand in the wetland was sparse. The aggressive growth of crack willows and their ability to colonise through their active vegetative reproduction has formed dense stands, allowing little understorey vegetation. Secondly the understorey transpiration under dense canopies with high leaf area and low energy flux is understood to be minimal and forms a minor component in water balance studies (Whitehead and Kelliher, 1991). It would be more significant in stands where the trees are widely spaced (Black and Kelliher, 1989; Kelliher et al., 1990). Therefore in the present study understorey transpiration was assumed to be minimal due to the above reasons and thus not included in the evapotranspiration estimation for the wetland water balance study.

4.2.2 Interception loss

During rainy periods, that part of the rain intercepted by the canopy of vegetation and evaporated directly back into the atmosphere is called interception loss. The rest of the rainwater reaching the ground either by dripping from the canopy and falling through gaps
is called throughfall. Interception loss is high, especially for aerodynamically rough vegetation of mixed forests, due to its high aerodynamic conductance, which may result in a high evaporation rate, compared to short vegetation. Interception amounts to 10 – 50% of the precipitation on forest, and accounts for an even higher percentage of the total water use of forests. Interception loss depends strongly on the timing, intensity of rainfall, vegetation structure and meteorological conditions controlling evaporation during and after rainfall (Klaassen et al., 1998; Chang, 2003; Muzylo et al., 2009).

The annual interception loss recorded in earlier studies of short rotation willow species is quite variable, ranging from 4 to 38% of evapotranspiration (Andersson, 1986, cited in Grip et al., 1989; Grip et al., 1989; Lindroth et al., 1994; Martin and Stephens, 2006). Interception loss for plantations, scrub and native forest in New Zealand is between 10 to 35% of precipitation. Similarly studies in New Zealand have shown that canopy interception can have a considerable effect on stream flow (Rowe et al., 2002). Estimates of groundwater flux were relatively insensitive to the mean canopy height, but more sensitive to leaf area index under various land cover types, showing the importance of interception loss (Finch, 1998; Fahey et al., 2001).

In the present study the rainfall passing through the canopy (throughfall) was measured under the crack willow canopy (located close to the evaporation pan) and gross rainfall was measured with a tipping-bucket rain gauge less than 200 m away in open area outside the wetland (Figure 3.10). Interception loss was estimated as the difference between gross rainfall (rainfall in open area) and throughfall (rainfall under the canopy). To reduce the error of estimated interception it is important to follow the standard method of spreading few rain gauges across the stand under the canopy. As the objective in the present study was to understand the water balance during dry periods (between rainfall events) it would not require a measurement of rainfall interception. Also there were lot of pratical problems in having required instrumentation for interception estimation. Therefore in the present study only one rain gauge was placed under the willow canopy to provide an understanding of the annual interception rate.

Stemflow is intercepted rain water reaching the ground running down the stems of trees. Stemflow is generally by far the smallest component of the interception balance. Studies
have shown the stemflow for *Pinus radiata* and *Douglas fir* plantation less than 5% in New Zealand (Fahey, 1964; Rowe, 1983; Rowe *et al.*, 2002). There are many studies suggesting it is small enough that it can be neglected (Rutter and Morton, 1977; Lankreijer *et al.*, 1993; Klaassen *et al.*, 1998; Rowe *et al.*, 2002). As stemflow was the smallest part of the interception process, and there being little evidence that it is high for willows and other broad leaved tree species in New Zealand, the stemflow was not measured in the present study.

### 4.2.3 Open water evaporation

Wetlands are typically located at low elevations, along streams and it is common to have a large extent of wetland moist all around the year with large areas under open water (Gippel, 2005). The present study wetland broadly falls into the category that is wetted by unregulated stream flows throughout the year, linked to rainfall events and helps in keeping the soil moist. The open water evaporation of the wetland was estimated based on pan evaporation measured under the willow canopy along with a visually recorded inundated area of wetland, and change in groundwater depth (depth-to-groundwater) recorded by a capacitance probe located in the centre of the wetland.

The open water area in the wetland was mainly along the stream passing through the wetland. It was difficult to manually estimate the open water area in the wetland due to high spatial and temporal variation. The spatial variation was mainly linked to the wetland topography and clogging of the stream by the crack willows. The temporal variation (particularly during the summer period) was linked to rainfall events. The spatial and temporal variation in open water area of the wetland stream was estimated based on the change in groundwater depth recorded by the Odyssey™ capacitance probe located in the centre of the wetland, and visual recordings of the wetland inundated area.

The change in groundwater depth recorded by the capacitance probe located in the centre of the wetland ranged from 795 to 1435 mm. This showed the wetland water level during the two years study period varied between 0 to 645 mm. The area covered by open water during the low flow period (< 910 mm) was estimated at 25% of the total wetland area, at medium flow (910-1070 mm) it was 50%, at high flow (1070-1210 mm) 75%, and at peak
flow (>1210 mm) it was 100%. The epan evaporation rate measured at 10 minute intervals under the willow canopy was applied to the estimated open water area of the wetland for a given period to estimate the open water evaporation rate of the wetland to be used in the water balance model.

4.2.3.1 Epan evaporation

The evaporation rate of open water for the wetland was based on the pan evaporation (epan) rate measured every 10 minutes. To represent the open water area of the wetland covered by dense canopy of crack willow the epan was placed under the canopy cover of willows (Figure 3.10). The evaporation rate from the epan is the amount of water evaporated (mm/day), which corresponds with the decrease in water depth for a given period. The main criticism of this technique is that storage of heat within the pan can be appreciable and may cause significant evaporation (Allen et al., 2000). Another criticism is the ‘edge effect’ of the epan, leading to higher evaporation rates (Davie, 2008). In the present study the epan was placed under the willow canopy in the centre of the wetland to overcome the above mentioned experimental errors.

The Class A epan was 120.7 cm in diameter and 25 cm deep. The pan was mounted on concrete bricks 40 cm above the ground and levelled. The evaporation pan was placed on load cells and the weight recorded by a ‘Campbell scientific automated CR10 logger’. Standard calibration procedures were followed to convert the load cells reading to an evaporation rate. The epan was filled with water which was not allowed to drop more than 12 cm below the rim. The evaporation rate was low under the tree canopy and during most of the heavy rainfall events the epan had overflowed. During the study period the water level was usually brought down in the epan (addition from rainfall), except during early February 2009 when water was added to the pan (2.5 cm). The reason for the water addition to the epan was that total rainfall was <27 mm (<16 mm throughfall) for the preceding 45 days during late December 2008 and January 2009.

The power required for the Campbell data logger and load cells was provided through solar panels for most of the study period. Solar panels were not able to meet the demand of power for load cells in winter (May to August) due to short winter days (insufficient sunshine hours). The additional power during this period was supplied through external
heavy batteries. The study area had wild boars and to protect the instruments it had two levels of fencing, an outer fence supported with electric fence. Plate 4.3 shows the epan, anemometer and rain gauge (under willow canopy) network in the centre of the wetland.

Plate 4.3 Epan, anemometer and rain gauge (under willow canopy) installed in the centre of the wetland

4.2.3.1.1 Calibration of epan load cells

The weight of the epan was measured with load cells which were calibrated and converted to water evaporation rate in depth (mm).

The epan was set up in the lab and placed on three load cells. The load cell readings for the empty epan were recorded and later readings recorded for every one litre of water added to the epan. To avoid random errors of measuring water in the measuring jar, it was weighed on an electronic balance and then added to epan. The regression relationship of load cell readings (average of three load cells) and volume of water added formed very strong regression relationship of $r^2 = 1.00$. This relationship was used to convert the load
cell readings to height of water in the epan and to estimate the evaporation rate of open water under the crack willow canopy.

To avoid any random errors of load cell readings the physical height of the water level in the epan was measured using a hook-gauge during frequent visits to the field. The hook-gauge had a pointed-end and it was possible to accurately record water level to 0.5 mm accuracy. The comparison of the hook-gauge readings and the calibrated load cell readings to height of water level in the epan showed an average difference of less than 1 mm.

4.2.4 Soil evaporation

Soil evaporation is often an important component of evapotranspiration, but is strongly dependent on energy flux, vapour pressure gradient, soil wetness and canopy cover. In most studies it was found to be less than 5% for closed canopy forests and neglected (Jones, 1992). However, Iritz et al. (2001) recorded soil evaporation of 23% of total evapotranspiration with an LAI varying from 0 (winter) to 7 (mid summer) for Salix viminalis clonal plantation (irrigated). Similarly, evaporation from the forest floor from broad-leaved forest accounted for 10 to 20% (Kelliher et al., 1992), and 25% for old-growth rainforest dominated by the conifer Dacrydium cupressinum (Barbour et al., 2005).

As soil dries the surface resistance increases, soil evaporation is reduced, and after a threshold is reached it is unimportant (McJannet et al., 1996). The main factor deterring the soil evaporation is low energy reaching the soil with high leaf area during peak summer periods. Fluxes from the forest floor are low during the growing season in deciduous forests (Moore et al., 1996), but are much higher in more open canopies (Lafluer, 1992; Baldocchi et al., 2000). In the present study the exposed soil (wetland area without open water) is wet all around the year, and earlier studies of soil evaporation in willow forests and forest floors in New Zealand (Kelliher et al., 1992; Iritz et al., 2001; Barbour et al., 2005) show the conditions are favourable for soil evaporation.

During field visits in peak summer although there was no standing water in large areas of the wetland, the soil was not dry. As the stream water level keeps dropping, so does the
soil water content but it then gets wet with regular rainfall events. This shows that as per
the study hypothesis, the wetland conditions are favourable for groundwater recharge even
during the peak summer period with high soil water content.

With the exposed soil in the wetland being wet all year round it would offer limited
surface resistance for evaporation, if the energy was available for soil evaporation. Due to
the deciduous nature of the crack willow stand and wet soil, the soil evaporation could be
high particularly between February to April due to the decrease in LAI (leaf shedding
period) and high incoming solar radiation. It is also understood that if there is energy
available under the willow canopy for open water evaporation from the epan, it would also
support the evaporation from the wet soil. Therefore it is considered that the soil
evaporation under the crack willow of the wetland would be significant and important to
include for accurate estimation of evapotranspiration for the wetland.

Part of the epan evaporation rate under the willow tree canopy was considered as soil
evaporation rate. In the FAO guideline of crop evapotranspiration estimation the soil
evaporation ranged from 0.25 to 0.40 of the reference crop evapotranspiration for crops
irrigated regularly through sprinkler, furrow and drip irrigation (Allen et al., 2000).
However, as the fraction of soil surface wetted in the wetland was higher than in
agricultural crops the soil evaporation would be higher. Based on earlier studies and the
sensitivity of the soil evaporation component in the Waihera wetland water balance
approach, it was assumed to be 50% of the open water evaporation rate (McJannet et al.,
1996; Allen et al., 2000). Also the energy available for soil evaporation under the canopy
of willow stand would be quite low as most of it would have been used up during the high
transpiration of willow trees.

4.3 Surface flow estimation

Surface water inflow and outflow from the study wetland are estimated through stream
gauging techniques. The water level was recorded using an Odyssey™ capacitance probe
that has resolution of approximately 0.8 mm. The velocity of the flowing water at different
stage heights was measured using an Ott current meter (Ott Corporation). This information
was used to establish a rating curve based on the relationship between discharge and stage
height, which was used to find real time surface inflow and outflow from the wetland. The discharge during low flows in summer was estimated using the bucket and stopwatch method. Other than the main ‘inlet’ at the top and ‘outlet’ at the bottom of the wetland there were two other inlets (‘north entry’ and ‘forest’) mainly providing surface water inflow throughout the year (Figure 3.10). Finally, the volumetric inflow and outflow (l/s) are expressed on an areal basis (mm) assuming the spread of water on to the 16 ha wetland.

There were problems in estimating the surface water flow during high flow levels due to the complexity of the site and other logistics.

- The major problem was finding a suitable outlet from the wetland for stream gauging. Once the flow exceeded 310 l/s it was not possible to do stream gauging as the flow spread unevenly across the wetland and there was no suitable gauging location further downstream. Therefore the outflow above 310 l/s was based on a best fit regression line worked out for flow measurements below 310 l/s. (Figure A1 in Appendix).

- The wetland is formed along the stream and is quite narrow (Figure 3.10). There were many (>20) inlets on either side of the wetland providing surface flow during rainy days and most of the winter season, which was difficult to measure with available resources. Therefore, due to the site complexity and shortage of resources, it was not possible to provide accurate inflow and outflow estimations for the wetland during high flows.

Given the problems of surface flow measurement, the residual estimation of groundwater flux using the water balance approach during high flows (winter) would be highly error prone. Therefore it was planned to conduct the water balance between two rainfall events during summer, as all the components of the water balance approach could be estimated or measured accurately. Occasionally the wetland was inundated by rainfall events during summer, which maintained a high groundwater table. This wetland setting was supposedly encouraging for groundwater recharge from the wetland.
4.3.1 Stream discharge estimation method

Using the velocity-area method, the stream discharge was estimated in two steps. The first step was to get a continuous measurement of surface runoff, *i.e.*, stage height (water flow level) recorded in 30 minute intervals using the Odyssey™ capacitance probe (Dataflow Systems Pty Ltd., Christchurch). For the second step a stage-discharge relationship or rating curve was prepared, where the discharge in the stream is related to the stage level through a series of runoff estimations using the velocity-area method. Finally the continuous runoff of the stream was estimated by linking the continuously recorded stage height with the rating curve.

In the velocity-area method, stream discharge was estimated as the product of the stream velocity and cross-sectional area of the stream profile (Weight and Sonderegger, 2001). The water depth and velocity measurements are taken along a transect perpendicular to the stream flow. It was important to select a measuring section for stream gauging, which was straight with uniform laminar flow conditions, a relatively flat stream bed, minimal flow obstruction from vegetation and rocks, no stagnant zones or divided channels and few or no eddies that hinder current meter movement. Usually the velocity of the water flow is never uniform in a given cross section of a stream due to friction from both the stream bed and the air above the stream (Gordon *et al.*, 2004). Therefore the stream cross section was divided into number of vertical sections of the same width, and velocity measured for each of them. For each section the width, water depth and average velocity was recorded. The width and depth measurements at different sections also help to get the profile of the stream cross section. The velocity of the stream flow was measured using the current meter. Generally 15-20 vertical sections across the stream are required for a good estimate of stream flow velocity (Gordon *et al.*, 2004). Each discharge segment should be less than 10% of the total discharge and the difference of velocities in adjacent segments should not be more than 20%. If the water flow is faster and deep, it was suggested to have smaller vertical sections (Gordon *et al.*, 2004). In each section using the current meter, average stream flow velocity was measured at 0.6 of the stream depth measured downward from the surface and the suggestions listed above were followed. The volume of water flowing in each vertical section was estimated as the product of measured velocity and area of vertical section. Finally the summation of discharge from all the vertical sections provided the total discharge or surface runoff for the stream. This is called mid-section velocity-area
method as velocity is measured in small vertical sections (Gordon et al., 2004). A rating curve was prepared by graphing several such discharge measurements for different stage heights. Later, a best-fit curve was worked out for these data points with the regression equation of the graph line corresponding to the relationship between stage and discharge.

There was a change in the cross section of the gauging location during high flows due to overflow of the stream. Therefore to create a best fit curve, separate low and high flow rating curves were developed for the inlets and outlet to estimate the discharge based on the stage height. The rating curves worked out for the inlets and outlet are presented in Appendix 1.

During summer with few rainfall events and high evapotranspiration, the surface flow levels were low and it was not possible to measure the velocity using the current meter. Therefore the discharge during low flow periods was measured using the bucket and stopwatch method. It involves the measurement of the time taken for a container of known capacity to be filled. The precautions suggested by Hauer and Lamberti (1996) that the container volume should take at least 3 seconds to fill and more than three readings taken to reduce measurement error were followed.

Stream discharge (Q) is calculated as

\[ Q = \frac{V}{t} \]

where \( V \) is the volume collected during time \( t \).
CHAPTER 5

5. WATER USE BY CRACK WILLOWS IN WETLAND

5.1 Introduction

This chapter will provide the results of measuring crack willow transpiration using the HPV sap flow technique. It will begin with a brief introduction and objective of the study and later will provide results and discussion on transpiration of willow trees. Initially willow transpiration will be understood with respect to size of trees, shading, and diurnal change in rates. Then sap flux densities of willows will be compared with other tree species to have a broader understanding of willow transpiration rates. The relationship between the transpiration of willows, PET and meteorological variables will be presented to understand the reliability of the HPV technique in the estimation of transpiration for willows. The chapter will also explain willow transpiration rates with respect to leaf phenology and soil water content. Finally factors determining the high transpiration rates of crack willows, and a summary of the chapter are provided.

Spread of Salix fragilis L. (crack willow) in wetlands of New Zealand has been a major environmental problem. It is one of the weediest willow species in New Zealand, and threatens many wetland and riparian sites. Invading crack willows are well known for their adverse impacts on channel blockages, flooding, structural changes in waterways, invading natural plant habitats, reducing animal and plant biodiversity and forming monocultures (Van Kraayenoord et al., 1995; Stanley and Ward, 2003).

Most of the willow tree species use large quantities of water through transpiration, reducing the freshwater availability for other in-stream and out-of-stream purposes. Both short-rotation coppice and naturally grown willows in riparian regions have shown high
transpiration rates (Cermak et al., 1984; Hall et al., 1998; ARMCANZ, 2000; Schaeffer et al., 2000; Doody et al., 2006). However there are no reliable estimates of transpiration rates for crack willow, which could be used in modeling the water use of the tree species. The only study done on crack willow by Cermak et al. (1984) in Czechoslovakia was for 2 days on 2 stems and does not account for the variation across the seasons and tree size class in the wetland. Most of the regional councils in New Zealand are presently in need of accurate water budgets for catchments and rivers due to ever increasing human demand for fresh water. Freshwater is a valuable resource and its conservation and efficient utilization are important for the development of the society, which requires reliable estimation of water use.

5.2 Study objectives

The objective of the study was the precise measurement of water use (transpiration) by a crack willow stand in the Waiwhero wetland over a period of one year using the HPV method. The transpiration estimation of crack willows will help in estimation of evapotranspiration for the wetland to conduct a water balance study to understand the groundwater flux. It is well known that the estimation of PET for a forested vegetation is complex due to stem anatomy, canopy structure, organic floor, root systems and for significantly affecting the water and energy transfers between ground and the atmosphere. A slight error in estimation of evapotranspiration would lead to an erroneous groundwater recharge estimates using a residual approach of water balance equation (Diodato and Ceccarelli, 2006). It was therefore important to estimate the evapotranspiration precisely, since it is one of the largest parameters of the water balance equation and highly error prone. This will help in improving the accuracy of modeling water balance studies at the catchment level for regional councils in New Zealand and also work out the net water savings from willow removal in the region with severe water scarcity.

5.3 Results and discussion

Transpiration by crack willows in the wetland was estimated through the HPV sap flow technique. For the present study, Greenspan Sap Flow Sensors (Model SF300, Greenspan Technology, Warwick, Australia) were used. The HPV method of sap flow estimation was
based on integration of a set of point estimates of sap flow velocity in the sapwood of individual trees.

Sap flow of a few sample trees representing the stand was measured and later scaled to the whole stand. Sap flow sensors were installed on 9 sample trees across the tree size class based on dbh determined through a vegetation survey. The sap flow velocity for the sample trees was recorded every 30 minutes for a period of 14 months from 4th February 2008 to 3rd May 2009. The annual transpiration results presented in this chapter are based on the first 12 months period (4th February 2008 to 3rd February 2009) sap flow data. A further three months data collected were used for estimating evapotranspiration of the wetland for water balance presented in chapter 6. A detailed description of the methodology followed in the estimation of transpiration rate of crack willows is presented in Chapter 4.

5.3.1 Variation of sap flow across the seasons

The variation of daily willow tree sap flow across the year was quite high, which was mainly dependent on the meteorological conditions and leaf phenology of trees. Figure 5.1 shows the typical sap flow for a single day during the respective period of the year. The last two letters (numbers) in the tree name is dbh (in cm). Typical sap flow for the year was represented by 9th March, 2008, low sap flow around winter transition period was represented by 23rd April, 2008 and peak sap flow in summer was represented by 28th December 2008. The representative day around winter transition (23rd April, 2008) also represents a typical day during early spring (September). The meteorological parameters and estimated transpiration per day for the three representative days is provided in Table 5.1 to understand the variation of sap flow. There was no rain around all three days selected for representation of sap flow across the year because sap flow will drop down greatly on rainy days due to low energy levels, and would not truly represent the season.
Figure 5.1 Diurnal sap flow variation on three representative days for the study period

Note: the two digit number in the tree ID is dbh (in cm)

Table 5.1 Transpiration and weather parameters for three representative days to understand the sap flow variation

<table>
<thead>
<tr>
<th>Date</th>
<th>Willow transpiration mm/day</th>
<th>PET mm/day</th>
<th>Solar radiation MJ/m²/day</th>
</tr>
</thead>
<tbody>
<tr>
<td>9/03/08</td>
<td>8.0</td>
<td>4.0</td>
<td>21.2</td>
</tr>
<tr>
<td>23/04/08</td>
<td>3.2</td>
<td>2.3</td>
<td>13.3</td>
</tr>
<tr>
<td>28/12/08</td>
<td>12.4</td>
<td>7.3</td>
<td>32.4</td>
</tr>
</tbody>
</table>

A fully automated climate station (around 4 km north-east of study site) was set up by Tasman District Council. The climatic parameters were recorded using ‘Campbell scientific automated logger - CR10’ (Campbell scientific Inc) and used to estimate the PET for pasture. The potential grass reference crop evapotranspiration was computed using the equation developed by Penman Monteith. Details of the derivation of this equation can be found in Monteith and Unsworth (1990). Some of the recommendations suggested by Smith (1991) were included as they were standards for use throughout the world by the FAO.
5.3.1.1 Influence of size and shading

The size of trees (dbh) and shading of canopy are among the important factors that influence sap flow rates of trees. The sap flow of bigger size trees of more than 50 cm dbh (~135 L/hr) is close to twice that of 40 cm dbh (~85 L/hr) trees during peak transpiration days of summer (Figure 5.1), whereas the differences in sap flow between the trees of lower than 40 cm dbh was not high. However just before the winter (April), the difference in sap flow between all size trees was uniform across the tree class. On a typical sap flow day (March) the difference in sap flow was slightly lower than that in peak summer (December). The variation of daily sap flow between the sample trees for the whole study period (230 days) is provided in Figure 5.2. Earlier studies have shown that dominant trees in a stand account for two-thirds of the total stand transpiration although they form one-third of stand population (Kelliher et al., 1992; Vertessy et al., 1997; Nadezhdina et al., 2002). This was also seen in the present study with high sap flow of largest crack willow tree in the wetland.

The non-proportional increase in transpiration rates between tree size class is not just based on dbh and leaf area but also on canopy exposure. Generally in a mixed age stand the mid-class (medium size) tree canopy is shaded partly and in lower class (small size) trees a large proportion of canopy is shaded. In the present study, a considerable proportion of sample trees with dbhs of 14, 22 and 39 cm were shaded and canopy of tree with dbh 25 cm was partly shaded. The results presented in Figure 5.1 and 5.2 show the sap flow of these trees are not increasing proportionally to the increase in dbh size of the sample trees. If these trees were not shaded, the sap flow would be higher than that recorded by the sap flow instruments. Therefore the explanation for non-proportional increase in sap flow rates between the sample trees exhibited across the size class was due to shading. However having said that the sap flow of a few sample trees was underestimated due to shading, it would be incorrect to say the up-scaled overall estimation of transpiration for the wetland was underestimated. Physically, most of the mid- and low-class willow trees in the wetland were partially or entirely shaded and sap flow would have been lower. The randomly selected sample trees with canopy partially and entirely shaded would truly represent the actual sap flow of the willows in the wetland for the respective tree size class. There are many studies suggesting sampling strategies to
be followed due to the variation in transpiration of trees within the stand. The most important is the tree size, but also it is important to select sample trees based on position of the canopy to receive the sun light (Cermak, 1989; Hatton and Wu, 1995; Lindroth and Cienciala, 1996). Cermak (1989) used the solar leaf equivalent as the basis for selecting the sample trees to represent the stand. Hatton and Wu (1995) developed a theory for scaling to account the dynamics of relationship between transpiration and leaf area due to light availability and size.

![Graph showing sap flow variation between sample trees](image)

**Figure 5.2 Mean daily sap flow variation between the sample trees for 230 days**

Note: there are no data presented for the winter period of 136 days

There are a large number of studies suggesting influence of canopy shading on the transpiration rates of trees. The study by Herzog *et al.* (1998) on large subalpine Norway spruce (*Picea abies*) in Switzerland showed that average estimated transpiration was about 3.5 times greater in the upper exposed canopy than the lower half. Transpiration also decreased 1.6 times from south to north. They found transpiration to be high in the tree parts coupled with free atmosphere. Similarly the study by Cermak *et al.* (1984) on crack willows found transpiration of exposed top crown to be ten times more than that of the shaded lower crown. Hall *et al.* (1998) observed systematic overestimation of sap flow rate for assumption of a constant proportionality between sap flow rates and leaf area of stand for scaling. The decline in the intensity of light as it passes down through the canopy
tends to limit the transpiration of smaller size tree class in the mixed age stands. The study by Lindroth and Cienciala (1996) on *Salix viminalis* found higher transpiration rates in dominant and co-dominant trees than understory trees. Similarly, the study by Kelliher *et al.* (1992) showed that 50% of the daily plot transpiration was from emergent red beech trees, mainly affected by tree social position, whereas, Lambs and Muller (2002) found sap flow in understory of *Salix alba* to be lower than overstory trees due to shading, but only for part of the study period. This clearly shows that within the tree there is a wide variation in transpiration of branches based on exposure to sun and coupling with free atmosphere.

### 5.3.1.2 Diurnal variation of sap flow

There is a wide diurnal variation in sap flow movement across the seasons due to changing weather conditions and tree species characters. From December to February due to long days and high energy levels, sap flow was at its peak around 10 AM and dropped to low levels around 10 pm (Figure 5.1). However, during April and September, sap flow reached a peak around 2 pm and dropped down to low levels by evening 6 pm. Around mid March sap flow reached a peak around 12 pm and dropped to low levels around 8 pm. There was a low level of sap flow occurring at night but this cannot be detected precisely by HPV technique.

Trees usually have water stores in stems, branches and leaves. These stores are generally emptied due to transpiration and are refilled at night time. The start of transpiration on the following day uses night stored water. This process of re-filling the tree water stores at night is called the re-hydration process (Hogg and Hurdle, 1997; Goldstein *et al.*, 1998; Müller, 2000). Therefore the night time sap flow movement does not necessarily indicate night time transpiration, but could be due to re-hydration.

There are some tree species additionally transpiring at night with supportive weather conditions (Irizar and Lindroth, 1994; Herzog *et al.*, 1998; Benyon, 1999; Musselman and Minnick, 2000). Other studies showed the response of stomatal closure to be linked to the production of plant hormones. The increased production of abscisic acid in the roots causes stomata to close in response to low soil water status as the soil dries both during day and night. On the other hand production of cytokinin hormones inhibit stomatal
closely stimulating night transpiration with soil conditions favourable for root growth with high soil water availability and VPD (Davies and Zhang, 1991; Whitehead, 1998). This act would increase the overall transpiration of the stand population along with high daytime transpiration during summer. However it would be difficult to confidently say, whether the sap flow movement at night was only refilling the depleted water stores in trees lost due to high day time transpiration or additionally transpiring at night. This issue is discussed in detail later in the chapter dealing with the relationship between transpiration and meteorological parameters.

5.3.2 Sap flux density

The sap flux density is the quantity of water flow across a known sap wood area per unit time. The mean and maximum sap flux density for the sample trees of different size is provided in Table 5.2. The maximum sap flow rate per hour was the highest record within the day. The sap flow was recorded every 30 minutes by the HPV instrument. Sap flux density would be the best parameter to compare the results with earlier studies on willows and other tree species, although there are both diurnal and seasonal variations. Sap flux density is the best parameter as it provides the sap flow rate per unit sapwood area for given time period. The sap fluxes on trees quoted by different authors are all in different units *viz.* per tree, areal basis, leaf area and biomass. Some provide little additional information to facilitate the comparisons and also different sap flow measurement techniques are followed.
Table 5.2 Mean and maximum sap flux density of sample trees over 24 hours period

<table>
<thead>
<tr>
<th>Tree ID</th>
<th>Average sap flow rate (L/h)</th>
<th>Max sap flow rate (L/h)</th>
<th>Sap wood area (m²)</th>
<th>Average sap flux density (L/m²/h)</th>
<th>Max sap flux density (L/m²/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>WZZ14</td>
<td>1.0</td>
<td>6.7</td>
<td>0.014</td>
<td>68.8</td>
<td>481.6</td>
</tr>
<tr>
<td>WKK20</td>
<td>2.7</td>
<td>11.1</td>
<td>0.025</td>
<td>107.6</td>
<td>447.2</td>
</tr>
<tr>
<td>WHH22</td>
<td>3.9</td>
<td>13.7</td>
<td>0.033</td>
<td>119.4</td>
<td>422.0</td>
</tr>
<tr>
<td>WEE25</td>
<td><strong>6.5</strong></td>
<td><strong>38.5</strong></td>
<td><strong>0.047</strong></td>
<td><strong>137.4</strong></td>
<td><strong>814.7</strong></td>
</tr>
<tr>
<td>WGG30</td>
<td>8.8</td>
<td>41.5</td>
<td>0.058</td>
<td>150.7</td>
<td>710.6</td>
</tr>
<tr>
<td>WFF36</td>
<td>10.3</td>
<td>52.3</td>
<td>0.066</td>
<td>156.0</td>
<td>794.8</td>
</tr>
<tr>
<td>WYY39</td>
<td>12.8</td>
<td>62.2</td>
<td>0.077</td>
<td>166.4</td>
<td>807.8</td>
</tr>
<tr>
<td>WDD42</td>
<td>15.7</td>
<td>86.1</td>
<td>0.087</td>
<td>179.8</td>
<td>988.5</td>
</tr>
<tr>
<td>WAA50</td>
<td>28.8</td>
<td>150.6</td>
<td>0.122</td>
<td>237.1</td>
<td>1239.1</td>
</tr>
</tbody>
</table>

Notes:
- The two digit number in the tree ID is dbh (in cm)
- WEE25 tree is in bold to highlight the sap flow rate of average sized tree

The sap wood area ranged from 0.014 to 0.122 m² for tree size from 14 to 50 cm dbh respectively and the sap wood area was 0.047 m² for medium sized tree with dbh 25 cm. Similarly, Cermak et al. (1984) found sapwood area (Salix fragilis) of 0.040 m² for a tree with dbh 25 cm and Schaeffer et al. (2000) found sapwood area (Salix goodingii) from 0.002 to 0.060 m² for trees with dbhs ranging from 7 to 37 cm respectively. This showed the sapwood area determined in crack willow for the present study was within the range as mentioned in earlier studies.

The average sap flux density varies from 68.8 L/m²/h for a 14 cm dbh tree to 237.1 L/m²/h for a 50 cm dbh tree. Similarly the maximum sap flux density also increases across the tree size class. For a medium sized tree of 25 cm dbh the average sap flux density was 137.4 L/m²/h and the maximum on a peak flow day (summer) was 814.7 L/m²/h. For a 50 cm dbh tree the average sap flux density was 237.1 L/m²/h and the maximum was 1239.5 L/m²/h. It is obvious that bigger size trees with a non-shaded canopy, and with a higher sap wood area and leaf area, will have a higher sap flux density than smaller size trees (Kelliker et al., 1992; Vertessy et al., 1997; Schaeffer et al., 2000; Vose et al., 2003).
Several sap flux density studies on willow species around the world show roughly the same rates. A two-day study by Cermak et al. (1984) on 25 cm dbh crack willow showed average sap flux density of 261 L/m²/h and a maximum rate of 1300 L/m²/h. Another study by Lambs and Muller (2002) on Salix alba for a 15 cm dbh tree using the heat balance method for a duration of 4 weeks found a sap flux density of 359 L/m²/h, which was at the higher end. A study by Schaeffer et al. (2000) presented a maximum sap flux density for Salix goodingii (15 to 25 cm dbh) in perennially flowing primary (514 L/m²/h) and dryer secondary channels (316 L/m²/h) of the San Pedro River, USA (Southeastern Arizona). This shows that roughly the annual average sap flux density was around 300 L/m²/h. However, when looking at above sap flux densities one needs to remember that there are wide differences in local climate, seasonal, diurnal, stand density, length of study period and technique used for study. However the above mentioned studies were all conducted on sites with an unlimited supply of water (wetland, perennial river channels and active river flood plain) as in the present study (wetland). The average sap flux density for a 25 cm dbh tree in the present study is quite low (137.1 L/m²/h) compared to those described above, which was mainly affected through length of study of period. The present study was conducted for 230 days and included the sap flow rates for a period after and before winter (autumn and spring), when the sap flow rate was quite low. Therefore it is apparent that the average sap flow rate would be low, when presented for long study periods. The earlier studies described above were all conducted for a short period during summer. The average sap flux density for a 25 cm dbh tree was 232.2 L/m²/h for the summer period (November to February), which falls within the range of sap flux density found in earlier studies.

The understanding of sap flux density in other tree species shows the sap flow rates of willow trees were quite high in the wetland. Extensive review of water use by 67 woody plant species using different methods showed less than 100 L/m²/h for trees with dbh less than 25 cm (Wullschleger et al., 1998). The sap flux density for plantation tree species Acacia dealbata (25 cm dbh) and Eucalyptus regnans (37 cm dbh) studied by Vertessy et al. (1995) was 88 and 139 L/m²/h respectively. The study by Olbrich (1991) on 41 cm dbh Eucalyptus grandis showed sap flux density of 195 L/m²/h. The sap flux density for conifers tree species viz., Pinus radiata (42 cm dbh) was 133 L/m²/h (Teskey and Sheriff,
1996) and Pinus pinaster (34 cm dbh) was 128 L/m²/h (Granier et al., 1990). The sap flux density of crack willows in the present study of 232.2 L/m²/h (25 cm dbh) when compared with the above studies is quite high. Therefore the up-scaled transpiration rate of the willow stands in the wetland could be high.

5.3.3 Annual crack willow stand transpiration

Vegetation sampling was conducted to understand the tree size distribution of crack willows in the wetland. Then the relationship of the form \( y=ax^b \) was computed between the tree biometric parameter dbh of sample trees (x) and daily sap flow rate (y) to understand the sap flow rate across the tree size class. Using this relationship sap flow rate measured on sample trees was scaled up to the stand level and presented in mm/day. A full description of the scaling procedure was presented in Chapter 4.

The average daily transpiration for crack willows in the Waiwhero wetland was 6.4 mm, and the total transpiration was 1477 mm. This comprised measurement of sap flow for 230 days and the low winter transpiration period from 28\(^{th}\) April to 10\(^{th}\) September 2008 was excluded from the study as there were no leaves or few leaves on the crack willow trees during this period\(^4\). The other reason to exclude the winter season sap flow data was the inability of the HPV technique to recognize low sap flow and zero flows correctly. The daily range of transpiration for the year was from 0.8 to 12.4 mm/day (Figure 5.3). The transpiration of willows was high during summer period compared to other periods. As the leaves of the willow trees started shedding in March (autumn) the transpiration started decreasing, and towards the end of April the transpiration was close to zero as there were no leaves on the crack willow trees. The trend was other way round in September and October (spring) as the leaves started flushing out after the dormant winter period. Monthly transpiration of crack willows in the wetland is provided in Table 5.3. Highest transpiration was recorded in January 2009 (315 mm), and February/December 2008 also transpired more than 235 mm. The lowest transpiration was recorded in April (83 mm) and September (49 mm). The standard error of transpiration of willow trees was 0.20.

\(^4\) Hereafter the study period of 230 days excluding the winter period 136 days will be referred as the ‘annual period’.
Figure 5.3 Daily variation of transpiration in relation to PET and rainfall

Note: there are no data presented for the winter period of 136 days

Table 5.3 Comparison of monthly transpiration of crack willows, and PET of grassland in the wetland

<table>
<thead>
<tr>
<th>Month</th>
<th>Number of days</th>
<th>Average transpiration mm/day</th>
<th>Total transpiration mm/month</th>
<th>PET mm/month</th>
<th>Ratio of transpiration and PET</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feb-08</td>
<td>29</td>
<td>8.1</td>
<td>236</td>
<td>114</td>
<td>2.1</td>
</tr>
<tr>
<td>Mar-08</td>
<td>31</td>
<td>5.7</td>
<td>178</td>
<td>83</td>
<td>2.1</td>
</tr>
<tr>
<td>Apr-08</td>
<td>27</td>
<td>3.1</td>
<td>83</td>
<td>48</td>
<td>1.7</td>
</tr>
<tr>
<td>Sep-08</td>
<td>20</td>
<td>2.4</td>
<td>49</td>
<td>48</td>
<td>1.0</td>
</tr>
<tr>
<td>Oct-08</td>
<td>31</td>
<td>5.0</td>
<td>154</td>
<td>109</td>
<td>1.4</td>
</tr>
<tr>
<td>Nov-08</td>
<td>30</td>
<td>6.4</td>
<td>192</td>
<td>130</td>
<td>1.5</td>
</tr>
<tr>
<td>Dec-08</td>
<td>31</td>
<td>8.8</td>
<td>272</td>
<td>168</td>
<td>1.6</td>
</tr>
<tr>
<td>Jan-09</td>
<td>31</td>
<td>10.1</td>
<td>315</td>
<td>186</td>
<td>1.7</td>
</tr>
<tr>
<td></td>
<td>230</td>
<td>6.4</td>
<td>1477</td>
<td>886</td>
<td>1.6</td>
</tr>
<tr>
<td>Standard error</td>
<td></td>
<td>0.20</td>
<td></td>
<td>0.13</td>
<td></td>
</tr>
</tbody>
</table>

Notes:
- Transpiration from May to August (winter period of 136 days) was excluded
- February consists of 26 days in year 2008 and 3 days in year 2009.
5.3.4 Relationship with potential evapotranspiration

The average daily transpiration of crack willows in the wetland (6.4 mm) was 1.64 times the daily average PET for grassland (3.9 mm). PET was estimated for grassland using the empirical equation of Penman Monteith based on climatic data collected 4 km from the study site. Details of this equation can be found in Monteith and Unsworth (1990). The peak PET was 7.4 mm/day, the lowest was 0.2 mm/day and the total for the annual period was 886 mm (Figure 5.3). Whereas annual transpiration of willows estimated through sap flow method was 1477 mm, the peak was 12.4 mm/day and lowest was 0.8 mm/day. This shows the ratio of annual transpiration of willows to PET was 1.7, but for summer period it was more than 2.0 (Table 5.3). Seasonally, the difference between PET and transpiration of willows was low during autumn (mid March to April) and spring period (September and October), as there were few leaves on the willow trees for transpiration. In the summer, however, the transpiration of willows was close to twice PET.

The above results of crack willow transpiration in wetland estimated as being close to twice the PET of grassland are largely in agreement with previous studies. The two day transpiration on two stems of crack willow in sedge-grass marsh (wetland) of Czechoslovakia showed water use of more than 4.1 mm day⁻¹, which was twice the PET (2.0 mm day⁻¹) estimated using the standard energy balance method (Cermak et al., 1984). Similarly, the transpiration of a clonal willow (Salix burjatica) plantation was twice the PET during the period of high soil moisture availability, net radiation and large humidity deficits (Hall et al., 1998). PET was estimated as reference crop evaporation as suggested by Shuttleworth (1993) using weather data. The study by Doody et al. (2006) on Salix babylonica transpiration in Yanco Creek system of New South Wales, Australia recorded evapotranspiration of 1989 mm for creek bed willows for a 12 month period. However evapotranspiration from open water calculated based on pan evaporation was 1642 mm for the 12 month period, which was 350 mm less than evapotranspiration of willows in the creek bed. This showed the creek willow transpiration for the 12 month period was 1.21 times higher than pan evaporation. Maximum daily transpiration rates of willows in the creek bed (permanently inundated) was 15.2 mm and those growing on elevated bank was 2.3 mm (not having unlimited access to water). On an average for the full year study period willows in the creek bed transpired six times higher than bank willows. The reason for the large difference between the creek bed willows and elevated bank willows was
mainly availability of soil water and low leaf area of bank willows. Also studies on many other riparian sites found the fast growing tree species transpired at twice the PET rates (Hall et al., 1998; Stephens et al., 2001; Vose et al., 2003).

The regression analysis provided an $r^2 = 0.76$ representing a linear relationship between PET ($x$) and transpiration ($y$) (Figure. 5.4). This relationship between the PET estimated for grassland through Penman Monteith equation and transpiration of willows estimated through sap flow technique was in the expected direction with both being driven by common meteorological parameters viz., solar radiation, VPD and wind speed. It is the generally believed that willow transpiration should be zero when PET for grassland was zero, but this was not always true. In the present study a closer look at daily transpiration rates showed PET estimated from the Penman Monteith equation to be zero during the late evening hours with low solar radiation, whereas willow trees in the wetland with sufficient soil moisture and supportive atmospheric factors transpired during the late evening hours (Iritz and Lindroth, 1994; Hogg and Hurdle, 1997; Goldstein et al., 1998; Müller, 2000; Musselman and Minnick, 2000). The role of re-hydration in the high transpiration of willows is discussed in detail in the latter part of the chapter. Therefore in the figure below the relationship was not forced through zero.

The reason for not achieving a significantly high linear relationship could be due to PET not being directly measured, but instead estimated using a large number of weather parameters for smooth grassland at 1 m above the ground using the Penman Monteith equation. The sap flow was directly measured for the rough canopy surface of the crack willow stand in wetland. It could be also due to the 4 km distance between the wetland covered by willows and the location of PET estimated. Also the difference between PET and transpiration was not the same across the study period. During autumn and spring due to few leaves on the willow trees the transpiration rates were low, although energy levels were high enough to support transpiration. PET during this period stayed higher because of the supporting meteorological conditions. In the study by Hall et al. (1998) the relationship between willow transpiration and PET was not uniform throughout the study period June to September. During the last couple of weeks in June and early July transpiration of willows was more than 2.5 times that of PET due to high solar radiation and sufficient soil moisture supporting high willow tree transpiration. Later in August,
after 21 days of no rain, willow trees were under water stress and due to low stomatal conductance the transpiration of willows was less than PET. Therefore in long-term studies covering different seasons the relationship between transpiration of trees and PET would not be highly significant.

Unlike grassland, the tree stands markedly change the sterometry (structure and morphology) of vegetation cover and increased the aerodynamic roughness along with light penetration. This would assist gust penetration and turbulence of wind, enhancing the removal of humid air accumulated on top of the canopy and atmospheric mixing. The study by Kelliher et al. (1992) showed aerodynamic conductance for momentum transfer of forest was proportional to wind speed. Similarly the review by Stephens et al. (2001) found tall crops with small leaves and rough canopies dependent primarily on wind speed and the humidity of the air above the vegetation being closely “coupled” with the atmosphere and resulting in high transpiration rates. In contrast short crops with uniform canopies tend to be “decoupled” from the atmosphere and transpiration was dependent predominantly on the intensity of incoming solar radiation. This shows the closure coupling of the atmospheric variables to the aerodynamically rough tree canopy increased transpiration rates of crack willows in the present study.
Figure 5.4 Linear regression relationship between daily PET and transpiration of crack willows

Note: the details of circled values of high and low transpiration are presented in Table 5.4 and 5.5 below to understand the reasons for being away from the best-fit line.

There were days with high willow transpiration and on the same days PET for grassland was quite low. To understand the reasons for those occurrences, three such days with high transpiration and low PET in early February have been selected (data points circled as ‘high transpiration’ in Figure 5.4) and compared with other days during the same period. A close look at the daily dataset showed most of these occurrences were during the peak summer period between December and February. The transpiration, PET, solar radiation and VPD from 8\textsuperscript{th} to 17\textsuperscript{th} February 2008 are presented in Table 5.4 and three days with a large difference between willow transpiration and PET are in bold. On a typical summer day, solar radiation was 20 to 25 MJ/m\textsuperscript{2}/day, grassland PET 4 to 5 mm/day and willow transpiration 8 to 10 mm/day. The main reason for PET to drop down (2 to 3 mm/day) on three selected days during the peak summer period was due to a decrease in solar radiation (15 to 20 MJ/m\textsuperscript{2}/day). However, on the same days transpiration of willows dropped down only slightly and stayed around 8 mm/day. The main reason for this high willow transpiration (despite the decrease in solar radiation) was a comparatively high VPD
between 0.62 to 0.81 kPa on these three days. Generally on a typical day during this period VPD lies between 0.50 to 0.60 kPa. Unlike grassland the aerodynamic roughness in a willow stand could also aid in high transpiration. On these days there could be additional energy (advective energy) driven from outside of the catchment into the wetland from adjacent catchments for such high rates of willow transpiration. The details of the influence through advective energy will be provided later in the chapter.

Table 5.4 High transpiration and low PET compared with other meteorological parameters for some days in February 2008

<table>
<thead>
<tr>
<th>Date</th>
<th>Transpiration mm/day</th>
<th>PET mm/day</th>
<th>Solar radiation MJ/m²/day</th>
<th>VPD kPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>8/02/08</td>
<td>9.0</td>
<td>5.3</td>
<td>28.1</td>
<td>0.75</td>
</tr>
<tr>
<td>9/02/08</td>
<td>9.3</td>
<td>3.8</td>
<td>21.6</td>
<td>0.81</td>
</tr>
<tr>
<td>10/02/08</td>
<td>4.0</td>
<td>1.8</td>
<td>12.2</td>
<td>0.51</td>
</tr>
<tr>
<td>11/02/08</td>
<td>9.5</td>
<td>4.0</td>
<td>20.9</td>
<td>0.97</td>
</tr>
<tr>
<td>12/02/08</td>
<td>8.4</td>
<td>2.9</td>
<td>18.0</td>
<td>0.62</td>
</tr>
<tr>
<td>13/02/08</td>
<td>8.2</td>
<td>4.8</td>
<td>25.9</td>
<td>0.61</td>
</tr>
<tr>
<td>14/02/08</td>
<td>7.2</td>
<td>2.5</td>
<td>13.3</td>
<td>0.60</td>
</tr>
<tr>
<td>15/02/08</td>
<td>6.0</td>
<td>2.1</td>
<td>13.7</td>
<td>0.35</td>
</tr>
<tr>
<td>16/02/08</td>
<td>7.9</td>
<td>2.4</td>
<td>15.1</td>
<td>0.74</td>
</tr>
<tr>
<td>17/02/08</td>
<td>10.0</td>
<td>5.0</td>
<td>25.9</td>
<td>1.08</td>
</tr>
</tbody>
</table>

Note: the three days with a large difference between willow transpiration and PET are in bold

Figure 5.4 shows that there were also days with low willow transpiration and high PET for grassland on the same days. These occurrences were during autumn (March and April) and spring (September and October) period. To understand the reasons for those occurrences three such days with low transpiration and high PET in late September were selected (data points circled as ‘low transpiration’ in Figure 5.4) and compared with other days during the same period. The transpiration, PET, solar radiation and VPD from 13th to 21st September 2008 are presented in Table 5.5 and three days with a large difference between willow transpiration and PET are in bold. On a typical day in late autumn and
early spring grassland PET/willow transpiration was 2.0 to 2.5 mm/day and VPD was 0.20 to 0.35 kPa. The main reason for low willow transpiration during the autumn and spring periods was the few leaves on the willow trees. The leaves of the willow trees started dropping in March and April (autumn) and the transpiration started decreasing. Similarly in September and October (spring) as the leaves started flushing out after the dormant winter period the rate of transpiration moved up. On the three selected days during mid September, PET (3.3, 3.5, 3.3 mm/day) raised with the increase in VPD (0.73, 0.57, 0.47 kPa) but there was not much change in the willow transpiration (2.0, 2.2, 2.3 mm/day). This shows PET during autumn and spring was mainly controlled by atmospheric parameters viz., VPD and solar radiation. Therefore the reason for the occurrences of days with high PET was the increase in VPD while willow transpiration rates were not affected with few leaves during spring and autumn period. However in general terms the transpiration was affected by available leaf area.

<table>
<thead>
<tr>
<th>Date</th>
<th>Transpiration mm/day</th>
<th>PET mm/day</th>
<th>Solar radiation MJ/m2/day</th>
<th>VPD kPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>13/09/08</td>
<td>1.5</td>
<td>2.3</td>
<td>13.3</td>
<td>0.49</td>
</tr>
<tr>
<td>14/09/08</td>
<td><strong>2.0</strong></td>
<td><strong>3.3</strong></td>
<td><strong>17.6</strong></td>
<td><strong>0.73</strong></td>
</tr>
<tr>
<td>15/09/08</td>
<td>2.0</td>
<td>2.5</td>
<td>16.9</td>
<td>0.55</td>
</tr>
<tr>
<td>16/09/08</td>
<td><strong>2.2</strong></td>
<td><strong>3.4</strong></td>
<td><strong>18.0</strong></td>
<td><strong>0.57</strong></td>
</tr>
<tr>
<td>17/09/08</td>
<td>1.4</td>
<td>1.2</td>
<td>8.6</td>
<td>0.31</td>
</tr>
<tr>
<td>18/09/08</td>
<td>1.3</td>
<td>1.0</td>
<td>7.2</td>
<td>0.21</td>
</tr>
<tr>
<td>19/09/08</td>
<td>2.1</td>
<td>2.8</td>
<td>16.9</td>
<td>0.34</td>
</tr>
<tr>
<td>20/09/08</td>
<td>2.8</td>
<td>2.0</td>
<td>11.9</td>
<td>0.33</td>
</tr>
<tr>
<td><strong>21/09/08</strong></td>
<td><strong>2.3</strong></td>
<td><strong>3.3</strong></td>
<td><strong>16.2</strong></td>
<td><strong>0.47</strong></td>
</tr>
</tbody>
</table>

Note: three days with large difference between willow transpiration and PET are in bold
5.3.5 Transpiration pattern in relation to meteorological parameters

It is well understood that transpiration rates of trees form a positive relationship with meteorological parameters, particularly solar radiation and VPD (Eamus et al., 2006). It is important to understand the relationship between the transpiration rates of willow trees estimated through the HPV technique and meteorological conditions as it would help to understand the ability of HPV technique in estimating transpiration rates. It would also provide alternative checks to estimating PET presented in the earlier section. The estimated PET was reference crop evaporation for grassland based on various meteorological parameters and therefore it is worthwhile to have a closer look at the variation in measured willow transpiration with changing meteorological conditions within the same day and span of a few days, as it could provide the reasons for high transpiration rates of willows.

Transpiration rates of trees is dependent on a combination of factors (a) meteorological conditions (solar radiation, precipitation, temperature, VPD, wind speed, advection and relative humidity), (b) physiological, structural, morphological and phenological character of trees (tree species, leaf area, leaf size, leaf stomatal function, root area and extent) and (c) soil water content (water availability at root zone, water holding capacity and permeability) (Kelliher et al., 1992; Boyer and Kramer, 1995; Hatton and Wu, 1995; Vose et al., 2003; Eamus et al., 2006). Transpiration is illustrated as being a Soil-Plant-Atmosphere continuum as it has to account for physical continuity of water as it moves from soil, through roots and up the tree to leaves, and out into the atmosphere (Vose et al., 2003; Eamus et al., 2006). The process of transpiration converting the liquid water in the leaves to a gaseous state requires significant input of energy, supplied through solar radiation. When water is readily available at the roots, most (90%) of the available energy is used to evaporate water from leaves. This shows solar radiation to be the largest and principal factor in determination of tree transpiration rates. However the transpiration process in addition to solar radiation will require atmospheric vapour pressure deficit and wind to influence the leaf boundary. One needs to remember that with all atmospheric factors supporting transpiration it is important for trees to have water readily available at roots to create the Soil-Plant-Atmosphere continuum for transpiration (Vose et al., 2003; Eamus et al., 2006). The above description on the process of transpiration shows that
willow transpiration in the study wetland with water readily available at the roots would form a strong positive relationship with solar radiation and VPD.

In Figure 5.5 it was clear that transpiration of willows, PET and solar radiation dropped down considerably during rainy hours. It is widely accepted that generally on rainy days the energy levels for transpiration will be low with low incoming solar radiation and high humidity (Kelliher et al., 1992; Kostner et al., 1992; Hall et al., 1998; Herzog et al., 1998; Lambs and Muller, 2002; Vose et al., 2003; Eamus et al., 2006). In contrast there are studies showing low levels of transpiration during rainy periods with high wind velocity and warm weather (Cermak et al., 1984; Herzog et al., 1998). In the present study also there were rainy periods with low levels of transpiration as can be seen in Figure 5.5 on 15th December 2008. It was supported by a slight increase in solar radiation and temperature during the rainy day. Later, on 16 December 2008 around 11.00 hours the rain stopped and as solar radiation increased, transpiration of willows followed the raise in less than 30 minutes. There was continuous rain from 8.00 to 11.00 hours with total rainfall of approximately 11.8 mm, sufficient to wet the whole canopy of the mixed age willow stand in the wetland. Generally lag time of few hours between increase in solar radiation and transpiration immediately after rainy period and on mornings with dew on leaves was found in most tree species (Cermak et al., 1984; Kelliher et al., 1992; Herzog et al., 1998; Lambs and Muller, 2002; Eamus et al., 2006). As leaves are wet, the available energy for transpiration was used to dry out the leaves and stomata were partially or fully closed during this period. In previous studies there was a large variation in lag time (0.5-3.0 hours) between the increase in energy levels and the start of transpiration after drying of the canopy. There are various factors involved viz., wind speed, turbulence, leaf area, leaf size, tree species, the rate of increase in energy levels and canopy architecture (Herzog et al., 1998; Vose et al., 2003; Eamus et al., 2006). In Salix alba the transpiration of trees increased immediately after rain with rapid increase in solar radiation with a lag time of less than 30 minutes (Lambs and Muller, 2002). In the present study the low lag time (<30 minutes) between increase in solar radiation and increase in transpiration of willows could be due to the smaller size of leaves, quick increase in solar radiation and high wind speed with turbulence.
There are a large number of studies supporting a lag time between the increase in energy levels in atmosphere and start of transpiration of trees, even on dry days and not just due to wet canopy (Cermak et al., 1984; Kelliher et al., 1992; Herzog et al., 1998; Lambs and Muller, 2002; Vose et al., 2003; Eamus et al., 2006). Trees generally have water stores used initially for transpiration as atmospheric energy levels increase in the morning and sap flow movement starts from the base of the tree with water drawn from the root zone after emptying the stores. This gives rise to the lag time between increase in energy levels in atmosphere and start of transpiration on dry days. However there was a large variation in lag time influenced by tree species, tree size, storage capacity, night transpiration, water supply at the root zone and environmental variables (Huntingford and Cox, 1997; Phillips and Oren, 1998; Meinzer et al., 2004). Cermak et al. (1995) found a time lag of 1-2 h between the increase in solar radiation and the start of sap flow at the base of the Scots pine and Norway spruce stem, suggesting that a significant amount of water (about 20%) from tissue storage was used for transpiration in the morning hours. Conversely, the study by Martin et al. (1997) found a small time lag in broad-leaved species compared to coniferous. Lag time was about 20 minutes for small broad-leaved crack willows as per the study of Cermak et al. (1984) and largely in agreement with the present study. On all three days (14, 16 and 17 December 2008) in Figure 5.5, when solar radiation increased transpiration followed it in less than 30 minutes. Crack willows stored about 3% (4 litres) of water inside the experimental tree, which is slightly more than one percent of the total tree volume (Cermak et al., 1984). This shows the storage capacity of crack willows is low and therefore stored water forms a small part of total transpiration of crack willows.

In the earlier part of the results section there was discussion on night time sap flow movement to refill (rehydrate) the depleted water stores of high day time transpiration in trees. It was difficult to interpret the results if it was all used to refill the empty stores in the trees, due to high transpiration during daytime or part of it was night time transpiration with supportive weather conditions. There are a large number of studies supporting night-time sap flow movement refilling the depleted water stores of high day time transpiration and a few tree species additionally transpiring at night with supportive weather conditions (Iritz and Lindroth, 1994; Hogg and Hurdle, 1997; Goldstein et al., 1998; Herzog et al., 1998; Benyon, 1999; Müller, 2000; Musselman and Minnick, 2000). In a willow stand
*(Salix viminalis)* mean transpiration rate at night time was 7% of day time rate and during peak transpiration period of two months it was around 30-35% (Iritz and Lindroth, 1994). On the other hand, Benyon (1999) showed high night time sap flow in *Eucalyptus grandis* was used partly for refilling water stores and the rest transpired as there was a significant correlation between night time sap flow and weather conditions conducive to keeping stomata open. Similarly, Oren *et al.* (1999) found VPD at night around 50% of day time and increasing sap flow movement at night following VPD in flooded *Taxodium distichum* forest. They further attributed the characteristic of night transpiration of hydric and mesic tree species with no soil water limitation was to take the advantage of carbon gain through photosynthesis is maximized. As described earlier crack willows in the current study site do not have large stores in the trees for water storage and therefore the sap flow movements at night need to be low. However, in contrast, in Figure 5.5 on 14, 16 and 17 December 08, although energy level for transpiration (solar radiation) dropped down to low levels around 20.00 hours, transpiration dropped down to less than 0.5 mm around 24.00 hours and continued the whole night, following the temperature gradient roughly. This suggests that a small portion of this sap flow movement after 20.00 hours was used for restoring the emptied stores of willow trees and the rest transpired at night. As described in the earlier part of the chapter the support for transpiration at night without solar radiation is attributed to various atmospheric conditions. The favourable soil conditions with high soil water availability at the root zone and high VPD with wind would stimulate transpiration of trees at night, even without solar radiation. The study by Herzog *et al.* (1998) recorded nocturnal sap flow on warm and dry wind nights, forcing stomata to remain open during night hours with unlimited supply of water for the trees. It is generally understood that VPD would be high on nights with warm and dry winds. In the present study with the wetland having sufficient water at the tree root zone, the stomata are kept open for transpiration with supportive meteorological variables (high VPD or advective energy). One of the reasons for high transpiration rates of willows compared to estimated PET rates for grassland could be the night-time transpiration and early start of sap flow in the morning with a small lag time.
Figure 5.5 Variation of hourly transpiration of willows and PET with changing meteorological variables for four days during summer (14 to 17 December 2008)

The relationship between the air temperature and transpiration in Figure 5.5 is not strongly correlated as seen with solar radiation and rainfall. As temperature was affected by cloud cover, wind, humidity and rainfall, it was difficult to predict transpiration of willows based on temperature.

There are many studies observing low stomatal conductance due to stomatal closure (partially or completely) to stop the high transpiration rates during mid noon to manage the leaf water balance as the soil water is low (Kelliher et al., 1992; Kostner et al., 1992; Herzog et al., 1998; Vose et al., 2003; Eamus et al., 2006). This was clearly shown in the cotton wood trees of a perennial and intermittent stream site in San Pedro River, USA by Gazal et al. (2006). They found at the peak of the dry period evidence of stomatal closure to avoid excessive transpiration in response to high VPD at the intermittent stream site with stomatal regulation for decline in leaf water potential caused by soil water limitation. In contrast, there was less apparent stomatal closure in response to high VPD (high transpiration) at the perennial stream site throughout the season. Transpiration appeared to be unaffected due to unlimited water supply. Interestingly there are also studies showing high stomatal conductance unaffected (till they reach the critical threshold) by soil water deficit and mainly controlled by the evaporative demand and plant species character (Braatne et al., 1992; Zhang et al., 1997; Hall et al., 1998). However, in the present study
with high soil water all year round in the wetland there was no stomatal closure to reduce the transpiration rates of crack willows during mid-day (Figure 5.5) as found in the study by Oren et al. (1999); Schaeffer et al. (2000); Gazal et al. (2006). There was no drop in the high transpiration rates during mid days of summer and was mainly following the energy levels above the tree canopy thus leading to high transpiration rates of willow stands.

5.3.5.1 Solar radiation

Solar radiation is considered the principal meteorological parameter supporting transpiration by trees (Eamus et al., 2006). The daily solar radiation data were collected from TDC climate station. The solar radiation was at its peak from December to February and so was the transpiration of the willow stand in the wetland and both largely followed the same trend during the study period (Figure 5.6). Transpiration dropped as solar radiation dropped on rainy days. However in autumn (March and April) and spring (September and October) the difference between the transpiration of willows and solar radiation was large compared to the peak transpiration period of the summer period. During the summer period transpiration of willows and solar radiation followed similar patterns (Figure 5.6). The main reason for the lowering of transpiration during autumn and spring was fewer leaves on willow trees compared to the summer period.

![Figure 5.6 Daily variation of willow transpiration in relation to solar radiation](image)

Transpiration of willow trees and solar radiation showed a strong linear relationship with \( r^2 = 0.72 \) (Figure. 5.7). This suggested that the transpiration of willows was high on days
with high solar radiation and dropped down as solar radiation dropped. However, transpiration need not be high on all days with high solar radiation as there are other factors *viz.*, VPD and wind speed affecting transpiration rates, which are all interlinked.

![Figure 5.7 Linear regression between daily transpiration of crack willows and solar radiation](image-url)

**Figure 5.7 Linear regression between daily transpiration of crack willows and solar radiation**

Note: the details of circled values of high and low transpiration are presented in Table 5.6 and 5.7 below to understand the reasons for being away from the best-fit line.

In Figure 5.7 there were days with high willow transpiration though solar radiation dropped down. It was clear from the daily dataset that these occurrences were few and most of them were during the peak summer period. To understand the reasons for such occurrences three such days with high transpiration and low solar radiation in late January were selected (data points circled as ‘high transpiration’ in Figure 5.7) and compared with other days during the same period.

On a typical peak summer day the willow transpiration was 8 to 10 mm/day, solar radiation was 20 to 25 MJ/m²/day and VPD was 0.40 to 0.60 kPa. The daily dataset in Table 5.6 shows the main reason for the high rate of transpiration was high VPD on three selected days (bold) although solar radiation dropped down. This shows that during the
peak summer period on some days although solar radiation was low (<15 MJ/m²/day) the willow transpiration was still high (> 7.4 mm/day) due to the high VPD (> 0.63 kPa). Therefore the reason for the occurrences of days with high transpiration was the high VPD on days with low solar radiation. Also on these days there could be additional energy (advective energy) from outside of the catchment into the wetland and aerodynamic roughness in the willow stand could have caused the high rates of willow transpiration.

Table 5.6 High transpiration and low PET compared with other meteorological parameters for some days in mid-summer

<table>
<thead>
<tr>
<th>Date</th>
<th>Transpiration mm/day</th>
<th>PET mm/day</th>
<th>Solar radiation MJ/m²/day</th>
<th>VPD kPa</th>
<th>Rain mm/day</th>
</tr>
</thead>
<tbody>
<tr>
<td>16/01/09</td>
<td>10.5</td>
<td>6.5</td>
<td>28.4</td>
<td>0.73</td>
<td>0</td>
</tr>
<tr>
<td>17/01/09</td>
<td>7.4</td>
<td>3.3</td>
<td>14.0</td>
<td>0.82</td>
<td>1.8</td>
</tr>
<tr>
<td>18/01/09</td>
<td>6.2</td>
<td>4.3</td>
<td>18.7</td>
<td>0.52</td>
<td>8.4</td>
</tr>
<tr>
<td>19/01/09</td>
<td>9.8</td>
<td>5.9</td>
<td>26.3</td>
<td>0.72</td>
<td>0.2</td>
</tr>
<tr>
<td>28/01/09</td>
<td>8.9</td>
<td>5.4</td>
<td>27.4</td>
<td>0.49</td>
<td>5.8</td>
</tr>
<tr>
<td>29/01/09</td>
<td>8.6</td>
<td>3.6</td>
<td>14.8</td>
<td>0.63</td>
<td>0</td>
</tr>
<tr>
<td>30/01/09</td>
<td>9.8</td>
<td>5.3</td>
<td>24.1</td>
<td>0.73</td>
<td>0</td>
</tr>
<tr>
<td>31/01/09</td>
<td>10.6</td>
<td>6.2</td>
<td>27.7</td>
<td>1.13</td>
<td>0</td>
</tr>
<tr>
<td>1/02/09</td>
<td>9.8</td>
<td>3.6</td>
<td>14.4</td>
<td>0.99</td>
<td>0</td>
</tr>
<tr>
<td>2/02/09</td>
<td>8.6</td>
<td>4.4</td>
<td>23.8</td>
<td>0.48</td>
<td>0</td>
</tr>
</tbody>
</table>

Note: three days with large difference between willow transpiration and solar radiation are in bold.

Figure 5.7 shows days with low willow transpiration solar radiation was quite high. To understand the reasons for those occurrences, four such days with low transpiration and high solar radiation in mid September were selected (data points circled as ‘low transpiration’ in Figure 5.7) and compared with other days during the same period. The daily dataset showed that most of the occurrences were during autumn and spring. The transpiration, solar radiation and VPD from 13th to 19th September 2008 are presented in Table 5.7 and four days with large difference between willow transpiration and solar radiation are in bold. On a typical day in late autumn and early spring willow transpiration
was 1.5 to 2.5 mm/day, solar radiation was 10 to 15 MJ/m$^2$/day and VPD was 0.20 to 0.40 kPa. The main reason for low willow transpiration during autumn and spring was few leaves on the willow trees. On the four selected days during mid-September solar radiation was high (> 16.9 MJ/m$^2$/day) and VPD also increased but there was not much change in the willow transpiration (2.0 to 2.2 mm/day). This shows willow transpiration rate during late autumn and early spring period was not affected by any increase in atmospheric parameters viz., VPD and solar radiation. The main reason for this low rate of transpiration was few leaves on the trees though supportive atmospheric conditions were present. This shows the significant role played by the leaf area.

<table>
<thead>
<tr>
<th>Date</th>
<th>Transpiration mm/day</th>
<th>PET mm/day</th>
<th>Solar radiation MJ/m$^2$/day</th>
<th>VPD kPa</th>
<th>Rain mm/day</th>
</tr>
</thead>
<tbody>
<tr>
<td>13/09/08</td>
<td>1.5</td>
<td>2.3</td>
<td>13.3</td>
<td>0.49</td>
<td>0</td>
</tr>
<tr>
<td>14/09/08</td>
<td>2.0</td>
<td>3.3</td>
<td>17.6</td>
<td>0.73</td>
<td>0</td>
</tr>
<tr>
<td>15/09/08</td>
<td>2.0</td>
<td>2.5</td>
<td>16.9</td>
<td>0.55</td>
<td>0</td>
</tr>
<tr>
<td>16/09/08</td>
<td>2.2</td>
<td>3.4</td>
<td>18.0</td>
<td>0.57</td>
<td>0</td>
</tr>
<tr>
<td>17/09/08</td>
<td>1.4</td>
<td>1.2</td>
<td>8.6</td>
<td>0.31</td>
<td>0.5</td>
</tr>
<tr>
<td>18/09/08</td>
<td>1.3</td>
<td>1</td>
<td>7.2</td>
<td>0.21</td>
<td>10</td>
</tr>
<tr>
<td>19/09/08</td>
<td>2.1</td>
<td>2.8</td>
<td>16.9</td>
<td>0.34</td>
<td>0</td>
</tr>
</tbody>
</table>

Note: three days with large difference between willow transpiration and solar radiation are in bold

### 5.3.5.2 VPD

VPD is one among a few meteorological parameters supporting transpiration and forming strong relationships (Cermak et al., 1984; Kelliher et al., 1992; Herzog et al., 1998; Wullschleger et al., 1998; Oren et al., 1999; Lambs and Muller, 2002). VPD is the difference between the saturation vapour pressure ($e_s$) and actual vapour pressure ($e_a$) for the period (Allen et al., 2000). VPD was not measured. Instead it was estimated using the equation from Allen et al. (2000) using daily maximum and minimum temperature and
relative humidity data. The required data for estimation of VPD were taken from the TDC climate station 4 km from the study site.

Daily crack willow transpiration rates and VPD follow the same trend for most of the study period (Figure 5.8) as it was with solar radiation. The VPD and transpiration of willows dropped on rainy days due to high relative humidity and low temperature with little support for transpiration. Secondly, the difference between the VPD and transpiration was not the same across the study period. During the high transpiration period of November to February both the daily transpiration of willows and VPD were high. However, there was a large difference between VPD and transpiration of willows from March to the last week of April (autumn) and early September to October (spring). This difference between daily transpiration and VPD was due to few leaves on the trees, as they got into dormancy in March and April. Similarly, in September and October it was linked to new leaves flushing out with the start of the spring season, with few leaves on the trees to support transpiration while VPD was high. Also the other reason for this difference was plots based on daily scale and not measured in same units.

![Graph showing daily variation of willow transpiration in relation to VPD](image)

**Figure 5.8 Daily variation of willow transpiration in relation to VPD**

The relationship between daily transpiration of willows and VPD could be better understood through regression analysis. The linear regression relationship between VPD and transpiration \( r^2 = 0.40 \) was not strong (Figure 5.9). One would expect a stronger relationship of VPD with transpiration of willows, as found with solar radiation \( r^2 = 0.72 \) and PET \( r^2 = 0.76 \). Also because solar radiation, air temperature, relative humidity and
wind speed are all interlinked meteorological variables (Vose et al., 2003; Eamus et al., 2006). The main reason for the weak relationship between transpiration and VPD could be an incorrect estimation of VPD, which was based on temperature and relative humidity measured over grassland. Other reasons could be as follows.

- As there was low leaf area (few leaves) in autumn and spring the transpiration of willows dropped greatly during this period though VPD was high.

- Meteorological parameters used in estimation of VPD were collected from 1 m above the smooth grassland, whereas transpiration was directly measured for rough canopy surface of crack willow stand in the wetland.

- It could be also due to the 4 km distance between the study wetland and site meteorological parameters collected for estimation of VPD.

![Graph](image)

**Figure 5.9 Linear regression between daily transpiration of crack willows and VPD**

Note: the circled values of high and low transpiration are discussed below to understand the reasons for being away from the best-fit line.

There were days when willow transpiration was high, but VPD was low. Four such days (data points) are circled as ‘high transpiration’ in Figure 5.9. A closer look at the daily dataset of these occurrences showed reasons that were similar to that found with solar
radiation discussed earlier. The reason for the occurrences of such incidents of high transpiration was high solar radiation during the day but with the VPD remaining small.

There were days with low willow transpiration but with the VPD remaining high. Three such days (data points) are circled as ‘low transpiration’ in Figure 5.9. A closer look at the daily dataset of these occurrences showed reasons that were similar with solar radiation. The occurrences of low transpiration with high VPD coincided with few leaves on the willow trees.

5.3.6 Effect of soil water content

The principal mechanisms involved in controlling the stomatal closure in response to reduced soil water and atmospheric water content are outlined schematically by Eamus et al. (2006) in Figure 5.10. Changes in stomatal closure represented the most reversible and fine tuned response of leaves to changes in atmospheric and soil water content. The flow chart showed atmospheric water content decline can cause stomatal closure, if water loss from leaves exceeded supply from roots. It was found that soil and atmospheric water content can interact to influence stomatal conductance additively or synergistically. As the present study is conducted in a wetland with high soil water content the flow of water from root zone to atmosphere will increase with the decrease in atmospheric water content, resulting in high rates of transpiration. Also to maintain the concentration gradient of water vapour pressure between the interior of the leaf and the atmosphere at the leaf boundary layer (leaf-to-air vapour pressure difference), the transpiration rates would be higher with unlimited supply of water at the root zone. Similarly, it was explained by Vose et al. (2003) and Eamus et al. (2006) that species exhibiting high leaf-level transpiration, leaf stomatal conductance and leaf water potential have the capacity to transpire large quantities of water.
Figure 5.10 Schematic of principal mechanisms involved in controlling the stomatal closure in response to reduced soil water and atmospheric water content

Note: redrawn from Eamus et al., 2006

5.3.7 Effect of leaf phenology

Leaf phenology plays a major role in the determination of transpiration rates along with meteorological parameters (Kelliher et al., 1992; Schaeffer et al., 2000; Lambs and Muller, 2002; Doody et al., 2006; Eamus et al., 2006). In the present study transpiration rate of willows in the wetland was greatly affected by leaf phenology during autumn and spring with meteorological conditions taking a secondary role during this period. There
was a large difference in transpiration between two days, with one representing an early spring day (2.0 mm/day) being five times lower than that representing a mid-summer day (9.7 mm/day) mainly affected by leaf cover (Figure 5.11). While meteorological parameters viz., VPD, solar radiation and air temperature were similar between the two days. During the dormant season of winter willow trees were devoid of leaves (Plate 5.1) and similarly later in first week of September (spring) the leaves started flushing with few leaves on the willow trees. By contrast, in the mid summer period the leaf cover was quite high as seen in Plate 5.2.

![Figure 5.11 Variation in transpiration due to leaf phenology on days with similar meteorological conditions](image)

The leaf cover percent was estimated with regular visual observations of the field site and scored on a scale of 0 to 100 percent, where 0 was mid-winter leaf cover and 100 was the mid-summer leaf cover. This information suggested leaf cover during March, April, September and October was on average 50 percent and particularly in April (40 percent) and September (30 percent) it was quite low (Table 5.8). In December and January leaf cover was around 100 percent supporting high transpiration rates in the willow stand, but in February the leaf shedding started and the leaf area was around 90 percent. To have more quantitative information the weight of leaves on evaporation pan with area of 1.14 m² was collected monthly (Table 5.8). The highest weight of leaves on the evaporation pan was found in April (448 gm/m²) and the lowest was September (39 gm/m²) (Plate 5.1). Similarly, a high range of weight of leaves was recorded in February (250 gm/m²) with
the start of the leaf shedding season and later in March (368 gm/m²) (Plate 5.2). October (73 gm/m²) and November (86 gm/m²) had a low weight of leaves collected on evaporation pan as this was period of new leaves flushing on the willow trees. Leaf area was around 100 percent in December and January but the weight of leaves on the evaporation pan was > 100 gm/m². This suggested that some of the older leaves had started shedding though new leaves were still formed but in the month of December and January.

**Table 5.8 Leaf phenology of crack willow stand in the wetland**

<table>
<thead>
<tr>
<th>Month</th>
<th>Leaf cover percent</th>
<th>Weight of leaves on evaporation pan gm/m²</th>
<th>Average transpiration mm/day</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feb-08</td>
<td>80</td>
<td>250</td>
<td>8.1</td>
</tr>
<tr>
<td>Mar-08</td>
<td>70</td>
<td>368</td>
<td>5.7</td>
</tr>
<tr>
<td>Apr-08</td>
<td>40</td>
<td>448</td>
<td>3.1</td>
</tr>
<tr>
<td>Sep-08</td>
<td>30</td>
<td>39</td>
<td>2.4</td>
</tr>
<tr>
<td>Oct-08</td>
<td>60</td>
<td>73</td>
<td>5.0</td>
</tr>
<tr>
<td>Nov-08</td>
<td>90</td>
<td>86</td>
<td>6.4</td>
</tr>
<tr>
<td>Dec-08</td>
<td>100</td>
<td>116</td>
<td>8.8</td>
</tr>
<tr>
<td>Jan-09</td>
<td>100</td>
<td>132</td>
<td>10.1</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td></td>
<td><strong>6.4</strong></td>
</tr>
</tbody>
</table>

Notes:
- During winter there were no leaves on the trees with weight less than 13 gm/m² in May 2008
- Leaf cover percent was based on visual observation
Plate 5.1 Crack willow stand without leaves with the start of winter

Plate 5.2 Crack willow stand with full leaf cover during mid-summer
The study by Eamus et al. (2006) described the variation of leaf area seasonally and with few leaves in the deciduous season when transpiration rates were low. Similarly, Schaeffer et al. (2000) showed that seasonal and patch-level variation in transpiration was related to phenological differences of willows and cottonwood trees species in San Pedro River, USA (Southeastern Arizona). They found transpiration to be negligible in early spring (April) and autumn (October). In both these studies leaf shedding was natural due to the deciduous forest type. On the other hand, there are studies showing variation in phenology due to extreme abiotic conditions. The shedding of leaves of black poplar due to summer drought decreased the transpiration rate by more than 50%, and later within a few weeks with the increase in soil moisture, the transpiration rate was back at seasonal peak (Lambs and Muller, 2002). Doody et al. (2006) showed a sudden drop in mean daily transpiration (for a few weeks) of creek willows from 11.9 to 5.5 mm/day, and bank willows from 1.8 to 0.6 mm/day, due to extremely hot dry days. Later partial recovery of transpiration was noticed as new leaves grew on the tree. However these types of extreme conditions are not noticed in New Zealand with its maritime location and the study area being in a wetland. It is apparent from earlier studies mentioned above and the present study that transpiration would be greatly affected from phenology of trees due to their deciduous nature during autumn and spring. Also during this period solar radiation, VPD and wind speed (meteorological parameters) would take a secondary role with its effect on transpiration in a deciduous stand. This can be seen more explicitly in Table 5.9, were autumn/spring months transpiration was lower than water equivalent of net radiation. In contrast, for summer months the transpiration of willows was higher than the water equivalent of net radiation. The main reason for low transpiration during autumn/spring was lower leaf area.

5.3.7.1 Leaf area index (LAI)

It is widely accepted that trees with higher LAI tend to transpire at higher rates with other supportive meteorological, physiological and structural conditions (Vose et al., 2003). Many studies show that sites with high soil water content typically had the highest LAI, although nutrient availability and temperature are also important in attaining maximum LAI (Long and Smith, 1990; Devakumar et al., 1999; Schaeffer et al., 2000; Gazal et al., 2006). In Salix viminalis the LAI above 2 was considered as closed canopy leading to high transpiration, but varied between 0 (start of winter) to 7 (mid summer) (Iritz et al., 2001).
However LAI remained between high during the peak transpiration period with no soil water deficit, indicating high transpiration rate (Lindroth et al., 1994). There were no direct attempts made in the present study to estimate the LAI of crack willows apart from the visual estimation of leaf area and weight of leaves on the evaporation pan (Table 5.8). However, based on the earlier studies showing high LAI for trees with high soil water content, for Salix tree species in particular, and with regular visual observation indicated a high LAI for the crack willow stand in the wetland. Therefore the high LAI during the peak transpiration period (summer) would result in high rates of transpiration for the crack willow stand.

5.3.8 Transpiration and energy flux

Evaporation of water requires energy, which is mainly in the form of solar energy (Allen et al., 2000). The transpiration process is governed by energy exchange at the vegetation surface and is limited by the amount of energy available. Therefore with this limitation it was possible to roughly predict the maximum potential transpiration rate of crack willows by applying the principle of energy conservation (Allen et al., 2000).

The energy arriving at the surface must equal the energy leaving the surface for the same time period through evaporation process. Energy required to evaporate 1 litre of water is 2.45 MJ at 20 °C (at 0.1 Mpa atmospheric pressure) and known as water equivalent of net radiation (Allen et al., 2000; Eamus et al., 2006). Therefore 1 mm of water evaporation over 1 hectare area requires 24500 MJ of energy.

The daily solar radiation data was collected from TDC climate station. Using the calculation procedures suggested by Allen et al. (2000) net solar radiation was estimated. Based on the energy flux the water equivalent of net radiation, transpiration of crack willow and PET and the ratios for each month of the study period are presented in Table 5.9. For April, September and October the transpiration was less than the water equivalent of net radiation. The main reason for the low transpiration during autumn and spring season was the lower leaf area. For the whole study period the difference between transpiration (1477 mm/day) and the water equivalent of net radiation (1416 mm/day) was less than 65 mm. It is therefore important to look the summer period in particular to
understand the high transpiration rates of willows, which was more than water equivalent of the daily net radiation and PET. The ratio of PET of grassland to water equivalent of net radiation on average from December to March was > 0.6 whereas the ratio of transpiration to water equivalent of net radiation for the same period was 1.2. The highest transpiration occurred in January with 315 mm, and PET was 186 mm. This showed that during the peak summer period, transpiration of willows was close to twice PET. While water equivalent of net radiation was 258 mm during same period in comparison to willow transpiration of 315 mm. A similar trend was followed in December, February and March. This showed maximum utilization of solar radiation and additional energy driven from outside of the catchment into the wetland for such high rates of willow transpiration. The additional energy driven into the wetland could be advective energy from adjacent catchments. The other main factor is the size and shape of the wetland. The study site is a narrow wetland formed along the tributary of Motueka River with an average width of around 100 m. The shape and size of the wetland makes it prone to the ‘clothes line effect’ by affecting the wind flow, availability of energy from surrounding areas and thus enhancing the rates of transpiration.

In the conversion of net solar radiation to water equivalent of net radiation, vertical energy fluxes are alone considered ignoring the net rate of energy being transferred horizontally, by advection (hot dry north westerly winds blowing during summer). This movement of horizontal energy fluxes would be higher in a narrow stretch of the wetland along the Waihero tributary and also having a ‘clothes line effect’ affecting the wind flow and enhancing the willow transpiration rates compared to grassland. This phenomenon is also referred as the ‘edge effect’ (Davie, 2008). Similarly there are many studies showing enhanced transpiration rates (higher stomatal conductance) due to dryness and warmth of the oncoming air currents (north westerly), i.e., by the advective sensible energy (Kelliher et al., 1992; Hall et al., 1998; Herzog et al., 1998; Eamus et al., 2006). The review by Stephens et al. (2001) showed that small isolated patches or thin strips of vegetation acting as a “clothesline” were able to transpire at 2.5 times the potential rate because of the availability of additional energy from surrounding areas (advective energy). This advective or “clothesline” effect played a potentially very important role where vegetation had access to unlimited water supplies.
Table 5.9 Comparison of transpiration of crack willows, water equivalent of net radiation and PET

<table>
<thead>
<tr>
<th>Month</th>
<th>Number of days</th>
<th>Monthly transpiration mm</th>
<th>Water equivalent of the net radiation mm</th>
<th>Ratio of transpiration and water equivalent of the net radiation</th>
<th>PET mm</th>
<th>Ratio of PET and water equivalent of the net radiation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feb-08</td>
<td>29</td>
<td>236</td>
<td>192</td>
<td>1.2</td>
<td>114</td>
<td>0.6</td>
</tr>
<tr>
<td>Mar-08</td>
<td>31</td>
<td>178</td>
<td>152</td>
<td>1.2</td>
<td>83</td>
<td>0.5</td>
</tr>
<tr>
<td>Apr-08</td>
<td>27</td>
<td>83</td>
<td>106</td>
<td>0.8</td>
<td>48</td>
<td>0.5</td>
</tr>
<tr>
<td>Sep-08</td>
<td>20</td>
<td>49</td>
<td>114</td>
<td>0.4</td>
<td>48</td>
<td>0.4</td>
</tr>
<tr>
<td>Oct-08</td>
<td>31</td>
<td>154</td>
<td>175</td>
<td>0.9</td>
<td>109</td>
<td>0.6</td>
</tr>
<tr>
<td>Nov-08</td>
<td>30</td>
<td>192</td>
<td>187</td>
<td>1.0</td>
<td>130</td>
<td>0.7</td>
</tr>
<tr>
<td>Dec-08</td>
<td>31</td>
<td>272</td>
<td>232</td>
<td>1.2</td>
<td>168</td>
<td>0.7</td>
</tr>
<tr>
<td>Jan-09</td>
<td>31</td>
<td>315</td>
<td>258</td>
<td>1.2</td>
<td>186</td>
<td>0.7</td>
</tr>
<tr>
<td>Total</td>
<td>230</td>
<td>1477</td>
<td>1416</td>
<td>1.0</td>
<td>886</td>
<td>0.6</td>
</tr>
</tbody>
</table>

To put the results of this study in context, Hall et al. (1998) found summer period daily transpiration rates on most days exceeding the water equivalent of the daily net radiation, implying negative sensible heat fluxes. Also Lindroth and Iritz (1993) found latent heat fluxes from a short rotation coppice of consistently higher than the net radiation at daily and even monthly time scales. These high rates were attributed to large aerodynamic and stomatal conductances imposing little restriction on evaporative fluxes. In fact some studies found stomatal conductances remaining higher despite an increasing soil water deficit, until a critical threshold deficit was reached, at which point the conductance dropped rapidly (Braatne et al., 1992; Hall et al., 1998). They attributed the high transpiration rates to canopy structure and the physiological characters of the tree species, which could be largely true in the present study.

Therefore in the present study the high transpiration rates could be attributed to combination of atmospheric conditions (advective energy), physiological character of the crack willows, and high soil water content.
5.3.9 Factors determining high transpiration rate in crack willow

It is well understood that the transpiration of crack willow stand in the wetland can be twice the PET estimated for grassland. It is largely accepted that a combination of factors drive high transpiration rates in trees compared to short vegetation and open water (Kelliher et al., 1992; Lambs and Muller, 2002; Vose et al., 2003; Eamus et al., 2006). With transpiration being under direct control of stomatal conductance, and the present study being in a wetland, the high soil water content would be the most important factor in enhancing the transpiration rates of crack willows, but it is not an absolute requirement (Vose et al., 2003; Eamus et al., 2006). Meteorological conditions (mainly horizontal energy fluxes), tree physiological characters (mainly leaf area) also played important roles and interacted with soil water content to drive the high rate of transpiration. Therefore it is important to summarize and list the role of various factors and their interaction in driving high transpiration of willow trees.

5.3.9.1 Study site location

The tree crowns of crack willows in a small narrow stretch of the wetland along the Waiwhero tributary would be influenced by the ‘clothes line effect’/‘edge effect’ affecting the wind flow and enhancing the transpiration rates compared to grassland. On such small narrow wetlands even low levels of horizontal energy fluxes (advection energy) would affect the transpiration rates considerably.

5.3.9.1.1 Soil water status

Night transpiration

The sap flow movement at night in crack willows with high soil water content increased the annual transpiration of willows to a large extent. With the wetland having sufficient moisture the stomata could have been signalled by the plant hormones to be kept open with supportive meteorological conditions, enabling carbon assimilation, on days with high VPD (nights with warm and dry winds).
**Mid-day transpiration**

There are many studies observing partial or full stomatal closure to stop high transpiration rates during mid-day to manage the leaf water potential as the soil water content decreases. However in the present study, with high soil water status all around the year in the wetland, there was no stomatal closure during the mid-day of peak transpiration period to reduce the transpiration rates of crack willows. In other words, to maintain the concentration gradient of water vapour between the interior of the leaf and the atmosphere at the leaf boundary layer, the transpiration rates would be high with unlimited supply of water at the root zone.

**5.3.9.2 Tree characters**

**Multi-stored canopy**

Unlike grassland, the tree stands markedly change the sterometry (structure and morphology) of vegetation cover and increase both the aerodynamic roughness and the exposure to radiation (light penetration). This aids in gust penetration and turbulence of wind, enhancing the removal of humid air accumulated on top of the canopy and atmospheric mixing. This showed the close coupling of the atmospheric variables to the aerodynamically rough tree canopy and increased the transpiration rates of crack willows compared to PET of grassland.

**High leaf area during peak transpiration period**

There is a strong linear relationship between leaf area and tree water use. With high soil moisture availability the LAI would be high during the growing season. Crack willow trees are devoid of leaves during the dormant season of winter, when the energy levels for transpiration are also low. As the energy levels for transpiration increase with the onset of spring (September) the crack willow trees also start with the flushing of new leaves. By mid-November the crack willow trees had a high leaf area and a sustained high leaf cover until the first week of March. Therefore with the high leaf area during the peak evapotranspiration period (summer) resulted in high transpiration rates of crack willow trees.
**Transpiration on rainy days**

It is largely accepted that generally on rainy days the energy levels for support of transpiration will be low or almost nil. With high relative humidity and leaf wetness the stomata are closed and no transpiration occurs. Conversely in the present study a low level of transpiration was observed just with the support of low energy levels.

There was a lag time (1-2 h) expected with the start of transpiration with an increase in energy levels on rainy days. However in the present study the transpiration of crack willows started with lag time of less than 30 minutes with the increase in the energy levels as the rain stopped. Similarly, the dew on the leaves had not affected the start of transpiration with the increase in energy levels during the peak transpiration period. This could be mainly attributed to the physiological characters of the crack willow trees.

**Tree water stores**

In the late evening after the drop in energy levels in the atmosphere, the sap flow movement in the trees refills (rehydrate) the depleted water stores caused by high day-time transpiration. Generally in most trees species the stored water is initially used for transpiration as atmospheric energy levels increase the next morning and water moves from the root zone after emptying the stores. This gives rise to the lag time between the increase in energy levels in the atmosphere and the start of transpiration on dry days (not due to wet canopy) in most tree species. However, there is large variation in lag time (1-2 h) influenced by tree species, storage capacity, night transpiration, water supply at root zone and environmental variables. In the present study of the broad-leaved crack willows the lag time was less than 20 minutes due to small water stores, and therefore resulting in high transpiration rate of willows.

**Other factors**

The other factors involved in defining the stomatal conductance and transpiration rates of willow trees are leaf CO₂ content, leaf temperature and leaf water status. However the main factors determining the tree water use are solar radiation, soil water content, tree physiological conditions, total leaf area, VPD and wind speed.
5.3.9.3 Meteorological parameters

High transpiration of crack willows was due to the optimal conditions following the concept of the Soil-Plant-Atmosphere continuum. There is a high availability of water at the root zone throughout the year, high leaf area during the peak transpiration period, high energy levels above the canopy, and long days. With these favorable environmental conditions the transpiration from trees would be at the highest levels, by providing the physical continuity of water to move from the soil to roots, then up the tree to the leaves and out.

Solar radiation

Solar radiation is one of the main meteorological parameter supporting transpiration. When water is readily available at the roots, most (90%) of the available energy is used to evaporate water from leaves. With high soil water status in the wetland year round, most of the available energy aids in transpiration of willows resulting in high rates.

Advection

The estimation of PET for grassland was done using the energy balance equation of vertical fluxes alone, with the net rate of energy transferred horizontally, by advection, being ignored. There are many studies showing enhanced transpiration rates (higher stomatal conductance) due to dryness and warmth of the oncoming air currents, i.e., by advective sensible energy. Small isolated patches or thin strips of vegetation acting as a “clothesline” are able to transpire at more than twice the potential rate because of the availability of additional energy from surrounding areas (advective energy). This advective and “clothesline effect” play a significant role in supporting high transpiration rates from vegetation with access to unlimited water supplies.

5.3.10 Summary

The spread of *Salix fragilis* L. (crack willow) one of the weediest willow species in New Zealand threatens many wetland and riparian sites. Invading crack willows are known for their adverse impacts on flooding, invading natural plant habitats and forming monocultures. Willows are also known in riparian regions for losing large quantities of
water through transpiration and thus reducing the freshwater availability for in-stream and out-of-stream purposes.

The size of willow trees based on dbh strongly influenced sap flow rates. The sap flow of bigger size trees of more than 50 cm dbh (~135 l/hr) was 1.58 times that of the 40 cm dbh (~85 l/hr) trees during peak transpiration days of summer, whereas the differences in sap flow between the trees of lower than 40 cm dbh was not high.

There was an uneven increase in transpiration rates with the increase in tree size and was dependent on the exposure of tree canopy to the aerial environment (shading of canopy). The sap flow of trees with dbh 14, 22 and 39 cm did not increase proportionally to the increase in size as a considerable proportion of canopy was shaded.

The average sap flux density varied from 68.8 L/m²/h for 14 cm dbh tree to 237.1 L/m²/h for 50 cm dbh tree. For a medium-sized tree of 25 cm dbh the average sap flux density was 137.4 L/m²/h. The study of sapwood area and sap flux density on willow species around the world were roughly around the same rates. However sap flux density for 25 cm willow tree in comparison to other tree species was quite high.

The transpiration of willow stand was high during summer and low around autumn and spring with few leaves. Monthly transpiration of crack willows in the wetland was highest in January (315 mm) and February/December transpiring more than 235 mm. The lowest transpiration was recorded in April (83 mm) and September (49 mm).

The average daily transpiration of crack willows in the wetland (6.4 mm/day) was 1.64 times of average PET for grassland (3.9 mm/day). This annual average was based on 230 days and the low winter transpiration period from 28th April to 10th September 2008 was excluded from the study as there were few leaves on the willow trees during this period. The annual transpiration of willows estimated through the sap flow method was 1477 mm. The highest rate was 12.4 mm/day and lowest was 0.8 mm/day. While annual PET was 886 mm, the highest rate was 7.4 mm/day and the lowest was 0.2 mm/day. Overall the ratio of annual transpiration of willows to PET was 1.7, but for the summer period it was
more than 2.0. Regression analysis ($r^2 = 0.76$) shows a linear relationship between PET and transpiration.

Solar radiation and VPD were at a peak from December to February and a similar trend was followed by transpiration. However, in autumn and spring the difference between the transpiration of willows and solar radiation/VPD was large compared to the peak transpiration period of summer. The main reason for this was the lowering of willow transpiration during autumn and spring with few leaves on willow trees compared to summer. The linear regression relationship between transpiration of willow trees and solar radiation was strong ($r^2 = 0.72$).

Maximum potential transpiration rate of crack willows was forecasted by applying the principle of energy conservation. Energy required to evaporate 1 litre of water requires 2.45 MJ at 20 °C (at 0.1 Mpa atmospheric pressure). Based on this principle the ratio of transpiration to water equivalent of net radiation on an average from the month of December to March was 1.2. During the study period the highest transpiration was found in January with 315 mm and the water equivalent of net radiation was 258 mm. A similar trend was followed in December, February and March, whereas in April, September and October the transpiration was less than the water equivalent of net radiation with a low leaf area in the willow stand.

A combination of factors affect high transpiration rates in the willow stand compared to short vegetation and open water. High transpiration from crack willows was due to the favourable environmental conditions following the concept of the Soil-Plant-Atmosphere continuum. The meteorological conditions (including the horizontal energy fluxes), tree physiological characters and high soil water content are the factors causing high transpiration rates from the willow stand in the wetland (listed in the earlier section of the chapter). The results of the measured transpiration of willow stand in the wetland will be presented in the context of a water balance study in the next chapter, to understand the groundwater flux.
CHAPTER 6

6. WETLAND WATER BALANCE AND GROUNDWATER FLUX

6.1 Introduction

This chapter will provide the results of a wetland water balance study to understand the direction of groundwater flux. It will start with an introduction providing the details of eco-hydrology, various ways of wetland groundwater interactions, as related to the objectives of the study. Later, results of the various components of the wetland water balance viz., precipitation, evapotranspiration (transpiration of crack willows, interception loss, soil and open water evaporation of wetland), surface water inflow and outflow will be provided. The main results of the chapter (a daily and monthly water balance) are used to understand the Waiwhero wetland groundwater flux. There is then an error analysis of the water balance components based on earlier studies. Finally the chapter concludes with an understanding of summer low outflow from the wetland and water savings if crack willows were not present on the wetland (open water wetland).

Water availability during summer is an important issue in the Moutere area of Tasman District, with significant amounts of groundwater abstraction for agricultural purposes. Groundwater abstraction has increased rapidly from the mid 1980s, after deep wells revealed large quantities of water from deeper aquifers (Davie et al., 2003). This has led to a full allocation of water resources in Moutere for summer (TDC, 2005). Presently the farming community in the Moutere is looking at groundwater as a potential resource for intensification of agriculture, and for any new area that needs to be brought under
cultivation. In this regard any new insights into the groundwater recharge for the Moutere aquifers would greatly help the regional council in its decision process of water allocation, and serve the needs of the farming community in the region. It is also important to understand the recharge mechanisms of the aquifers for the better management of the recharge zones and for sustainable management of water resources.

To estimate the groundwater recharge to the Moutere aquifers from the Rosedale Hills a water balance study was conducted under two main land covers: pasture and *Pinus radiata* (Davie *et al.*, 2003). The study revealed that under the present land cover of the Rosedale Hills, groundwater recharge (up-scaled from small study catchments) was quite low, but it was hypothesized that diffuse low infiltration over a large area of the Rosedale Hills could add large volumes of water to the deep aquifers in the Moutere region. However, Davie *et al.* (2003) did not include the wetlands located within the Rosedale Hills which could be playing a pivotal role in recharging the aquifers in the Moutere region. Some support for the idea that the Waiwhero wetland recharges Moutere groundwater is the generalization that wetlands frequently replenish aquifers and are often located within the recharge zone of the aquifers (Meyboom, 1966; Winter and Rosenberry, 1995; Winter, 1999; Bullock and Acreman, 2003; Schot and Winter, 2006; Todd *et al.*, 2006).

The Waiwhero wetland (16 ha) is a large wetland in the potential recharge catchment area (Rosedale hills) for the Moutere deeper aquifers (Thomas, 1989). Although the wetland falls within the Motueka River surface water catchment it is understood that due to the hydro-geological linkages, the infiltrating water is moving across the catchment boundary into the Moutere aquifers (Thomas, 1989; Stewart and Thomas, 2002; Davie *et al.*, 2003). The evidence for this conclusion was the high permeability of the Rosedale gravels and potentiometric surveys of borewells in the Moutere valley which indicated a flow direction from the Rosedale hills. This supported the hypothesis that the Waiwhero wetland replenishes the aquifers and the groundwater recharge has been recognized as an important function of wetlands (Meyboom, 1966; Winter and Rosenberry, 1995; Winter, 1999; Bullock and Acreman, 2003; Schot and Winter, 2006; Todd *et al.*, 2006).
6.1.1 Wetland eco-hydrology

Wetlands hold important conservation, ecological, aesthetic, biodiversity and economic value. They provide ecosystem services like water storage, flood mitigation, groundwater recharge, sediment stabilization, low flow regulation, and natural retention of some pollutants and nutrients (Clarkson et al., 2004). However, these systems are increasingly threatened by human interferences which have led to the disappearance of a large proportion of the world’s wetlands. This has prompted the development of means for their sustainable management, and therefore it is important to understand the behaviour of wetlands particularly in eco-hydrological terms (Bullock and Acreman, 2003 and Eamus et al., 2006). There are strong linkages between wetland hydrology and plants (Bullock and Acreman, 2003; Campbell and Jackson, 2004). The hydrological conditions of the wetland are also largely controlled by plants through building peat, transpiration, affecting the flow of water, trapping sediments and erosion control.

The Waiwhero wetland is mainly covered by crack willows which are well known for their physiological adaptations and ecological resilience (SRCMA, 2007). They are extensively used in ecosystem restoration work and are used as a cost-effective river bank stabiliser. The main problem caused by willows is their invasive growth and colonisation of river and stream beds, and hence they are categorised as a weed. Another major detrimental character of willows is their reputed capability of high transpiration, as demonstrated in previous chapter 5. With this background the present study will try to understand the effect of willows on the hydrological services provided by the wetlands.

6.1.2 Wetland groundwater and surface water interaction

It is well understood that groundwater and surface water interactions in wetlands are highly dynamic. They are temporally and spatially complex with some wetlands acting as recharge, discharge zones or even interchange between the seasons (Townley and Trefry, 2000; McEwan et al., 2006). A detailed discussion of wetland groundwater and surface water interaction is presented in Chapter 2 (Section 2.4).

Wetland groundwater and surface water interactions are mainly controlled by local hydro-geomorphology, climate, vegetation, climate and wetland management (Rosenberry and
Winter, 1997; Winter, 1999; McEwan et al., 2006). There are a large number of studies establishing the role of wetlands in groundwater recharge (Winter and Rosenberry, 1995; Winter, 1999; Bullock and Acreman, 2003; Schot and Winter, 2006; Todd et al., 2006). However, the review of wetland hydrological studies by Bullock and Acreman (2003) found a good number of studies with significant contrasts, which was quite different from the long-standing generalization that wetlands always provide groundwater recharge. The studies by Gilvear et al. (1993), Gilvear et al. (1997), and Raisin et al. (1999) showed that wetlands serve as discharge zones in certain hydro-geological settings like high water tables and high evapotranspiration rates. On the other hand there, are studies showing wetlands as both recharge and discharge zones dependent on seasons. The recharge-discharge function of most wetlands greatly changes both temporally and spatially due to various hydrogeological and climatic conditions (Gerla and Matheney, 1996; Grapes et al., 2006; Harvey et al., 2006).

It is widely understood that high evapotranspiration and especially transpiration of phreatophytic vegetation causes groundwater discharge into the wetland apart from hydro-geological setting (Meyboom, 1966; Cermak et al., 1984; Harvey et al., 2006; McCarthy, 2006). Thus high evapotranspiration reduces the groundwater recharge from wetlands and works against the long-standing generalization that wetlands always provide groundwater recharge. This suggests that the Waiwhero wetland covered with crack willows and with high evapotranspiration (see Chapter 5) and due to geological setting might act as a discharge zone in contrast to the study hypothesis that it is a recharge zone for aquifers in the Lower Moutere. The results presented in this chapter will help in understanding the role of the wetland groundwater flux (recharge or discharge).

6.1.3 Objectives

The objective of the wetland water balance approach is to understand the role of the wetland as a possible recharge zone for Moutere aquifers. However, based on the results in Chapter 5, due to the high transpiration of willows, the wetland could be acting as a discharge zone. This part of the study will attempt to decipher between the two conflicting wetland theories of recharge and discharge (groundwater flux). It will also provide more precise information for environmental managers on groundwater gains/losses from the
wetland for developing a sustainable management plan to meet the needs of the community, and for the economic development in the region.

6.2 Results and discussion

6.2.1 Wetland water balance variables

The fundamental water balance equation states that the amount water entering a region must be equal to the amount of water leaving plus the change in the amount of water stored. Groundwater flux for the wetland is estimated using the residual water balance equation 2.1 below.

\[
\text{Groundwater flux} = \text{Inputs} - \text{Outputs} \pm \Delta S
\]

Equation 2.1

Inputs = precipitation + surface inflow

Outputs = evapotranspiration + surface outflow

\(\Delta S\) = change in wetland water storage over time

It is well understood that accurate estimation of all of the components of the water balance equation helps in reducing the magnitude of errors (Scanlon et al., 2002; Ranjan et al., 2006). However this is not always possible due to the difficulties in making hydrologic measurements (Carter, 1986). The water balance approach of this study will not estimate the change in wetland groundwater as it is highly dynamic. Groundwater in the wetland could be linked with sub-surface flow and water moving in either direction from the Moutere aquifers. Given these complex groundwater linkages, in the present study the groundwater flux (recharge or discharge) in the equation will be estimated as a “residual”, whereas all other components of the water balance equation are measured or estimated. Therefore the study will not measure the groundwater inflow and outflow for the water balance approach.

The above water balance approach will help to understand the groundwater flux. The Waiero wetland would be providing the groundwater recharge if precipitation and surface inflow together are more than evapotranspiration and surface runoff losses. By contrast, if evapotranspiration and runoff losses are more than precipitation and surface inflow, then it would be groundwater discharge. If the latter is true it is not possible to
accurately pin-point the source of groundwater discharge into the wetland. The possible sources could be a combination of sub-surface inflow from the local region (shallow soils of surrounding hills) and from shallow and deep aquifers. In contrast, if the results show the wetland as a recharge zone it would be recharging the Moutere aquifers being located within the aquifer recharge zone, as hypothesised in earlier studies (Thomas, 1989; Stewart and Thomas, 2002; Davie et al., 2003).

In the sections below the results of each component of the water balance approach viz., precipitation, evapotranspiration (transpiration of crack willows, interception loss, soil and open water evaporation of wetland), surface water inflow and outflow results, will be provided.

6.2.1.1 Time step of water balance study

This section provides the details of time step of water balance results presented in the chapter. The main problem was estimating the surface water flows during high flow levels due to complexity of the site and other logistics. The Waihero wetland is formed along the stream and is quite narrow (Figure 3.9 and 3.10). There were many (>20) inlets on either side of the wetland providing surface inflow on rainy days and most parts of the winter, which were difficult to measure. Secondly, it was not possible to find a suitable outlet for wetland stream gauging after outflow volume exceeded 310 l/s due to the uneven spread of water across the wetland. Given the problems of surface flow measurement, the residual estimation of groundwater flux using the water balance approach during high flows (winter and around rainy days) was not possible. This also ties in with the summer estimation of transpiration of willow trees in the Waihero wetland presented in Chapter 5. Therefore it was planned to conduct the water balance for summer only, as all the components of the water balance approach were estimated or measured as accurately as possible. Occasionally the wetland was inundated with rainfall events during summer, causing a high groundwater table, and maintaining a wet soil fraction all around the year.

Water balance results are normally presented in various time steps e.g. hourly, weekly, monthly and annually. In the present study due to constraints mentioned above the water balance results are provided for two summer periods (2008 and 2009) at daily and
monthly intervals, although the data were collected continuously at 30 minute resolution for the two year period (Table 6.1). It is important to note that the monthly water balance results do not include those days with surface water flow affected by rain. This was done to avoid the unaccounted high flows during rainy days.

Table 6.1 List of months included in the summer period for 2008 and 2009 for providing water balance results

<table>
<thead>
<tr>
<th>Summer period for 2008</th>
<th>Summer period for 2009</th>
</tr>
</thead>
<tbody>
<tr>
<td>December 2007</td>
<td>December 2008</td>
</tr>
<tr>
<td>January 2008</td>
<td>January 2009</td>
</tr>
<tr>
<td>February 2008</td>
<td>February 2009</td>
</tr>
<tr>
<td>March 2008</td>
<td>March 2009</td>
</tr>
</tbody>
</table>

6.2.1.2 Precipitation

Precipitation is the easiest component in the water balance to measure with least error when compared to other variables like evapotranspiration and surface water flow. The annual rainfall for 2008 at the study site was 1354 mm, and 1297 mm at the TDC raingauge (Figure 3.9). However, the annual average rainfall for 14 years at TDC raingauge was 1116 mm/yr, which is 21% lower than the study year. The high rainfall for the study year was mainly due to high winter rainfall (April, July, August and September). Another irregular event during the study period was low rainfall (4 mm) in November 2007. However the heavy rain in October 2007 (206 mm) and December 2007 (95 mm) was enough to compensate the dry period of November 2007 (Table 6.2).

As the study was concentrating on the summer period it is important to look at rainfall variations across the two periods. The summer period (December to March) for the year 2008 was 318 mm and for the year 2009 it was 335 mm, whereas the average 14 year summer period rain at TDC raingauge was 288 mm. This shows the rain at the study site was 10% (year 2008) and 16% (year 2009) higher compared to an average year. However, overall the rain at the study site for the two summer periods was close to average year rainfall.
Table 6.2 Monthly and summer period total rainfall and direct rainfall contribution on the wetland

<table>
<thead>
<tr>
<th>Month/Year</th>
<th>No of days</th>
<th>Rainfall mm</th>
<th>Summer period rain mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oct-07</td>
<td>31</td>
<td>206</td>
<td></td>
</tr>
<tr>
<td>Nov-07</td>
<td>30</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>Dec-07</td>
<td>31</td>
<td>95</td>
<td></td>
</tr>
<tr>
<td>Jan-08</td>
<td>31</td>
<td>79</td>
<td></td>
</tr>
<tr>
<td>Feb-08</td>
<td>29</td>
<td>53</td>
<td></td>
</tr>
<tr>
<td>Mar-08</td>
<td>31</td>
<td>92</td>
<td></td>
</tr>
<tr>
<td>Apr-08</td>
<td>30</td>
<td>178</td>
<td></td>
</tr>
<tr>
<td>May-08</td>
<td>31</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>Jun-08</td>
<td>30</td>
<td>108</td>
<td></td>
</tr>
<tr>
<td>Jul-08</td>
<td>31</td>
<td>164</td>
<td></td>
</tr>
<tr>
<td>Aug-08</td>
<td>31</td>
<td>175</td>
<td></td>
</tr>
<tr>
<td>Sep-08</td>
<td>30</td>
<td>140</td>
<td></td>
</tr>
<tr>
<td>Oct-08</td>
<td>31</td>
<td>84</td>
<td></td>
</tr>
<tr>
<td>Nov-08</td>
<td>30</td>
<td>125</td>
<td></td>
</tr>
<tr>
<td>Dec-08</td>
<td>31</td>
<td>139</td>
<td></td>
</tr>
<tr>
<td>Jan-09</td>
<td>31</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>Feb-09</td>
<td>28</td>
<td>122</td>
<td></td>
</tr>
<tr>
<td>Mar-09</td>
<td>31</td>
<td>54</td>
<td></td>
</tr>
<tr>
<td>Apr-09</td>
<td>30</td>
<td>95</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td><strong>318</strong></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td><strong>335</strong></td>
</tr>
</tbody>
</table>

6.2.1.3 Evapotranspiration

The entire surface and subsurface water released from a wetland into the atmosphere through the process of evaporation and transpiration is known as evapotranspiration. The major components of evapotranspiration for a forested wetland are the sum of tree transpiration, interception evaporation by the canopy, soil and open water evaporation. The present study attempted to measure the major components using different methods. Refer to equation 2.2 for the evapotranspiration equation used in the study.
6.2.1.3.1 Transpiration

Transpiration is the loss of water from plants in the form of vapour through the stomata. Using the HPV technique transpiration from representative individual trees are measured and extrapolated to the stand level (Granier, 1987; Cermák et al., 1995; Martin et al., 1997). The extent of transpiration by crack willows in the wetland has been presented in the Chapter 5.

The annual average daily transpiration (230 days in 2008) of crack willows in the wetland (6.4 mm/day) was close to twice the PET for grassland (3.9 mm/day). The low winter transpiration period from 28th April to 10th September 2008 was excluded as there were no leaves or few leaves on the crack willow trees during this period. The range of transpiration across the year was from 0.8 to 12.4 mm/day (Figure 6.1).

The transpiration of willows was high during summer compared to other seasons. As the leaves of the willow trees started dropping in March (autumn) the transpiration started decreasing’ and towards the end of April month the transpiration was quite low as there were no leaves on the crack willow trees. Again later in October (spring), as the fresh leaves started flushing out after the dormant winter period, the transpiration increased and peaked during mid summer (Figure 6.1). Monthly transpiration of crack willows in the wetland is listed in Table 6.3.
Table 6.3 Monthly and summer transpiration

<table>
<thead>
<tr>
<th>Month/Year</th>
<th>No of days</th>
<th>Transpiration mm/month</th>
<th>Average transpiration mm/day</th>
<th>Summer transpiration mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oct-07</td>
<td>31</td>
<td>155.4</td>
<td>5.0</td>
<td></td>
</tr>
<tr>
<td>Nov-07</td>
<td>30</td>
<td>201.7</td>
<td>6.7</td>
<td></td>
</tr>
<tr>
<td>Dec-07</td>
<td>31</td>
<td>189.1</td>
<td>6.1</td>
<td></td>
</tr>
<tr>
<td>Jan-08</td>
<td>31</td>
<td>233.6</td>
<td>7.5</td>
<td>Total in summer = 828.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Avg per day = 6.8</td>
</tr>
<tr>
<td>Feb-08</td>
<td>29</td>
<td>228.9</td>
<td>7.9</td>
<td></td>
</tr>
<tr>
<td>Mar-08</td>
<td>31</td>
<td>177.2</td>
<td>5.7</td>
<td></td>
</tr>
<tr>
<td>Apr-08</td>
<td>30</td>
<td>85.3</td>
<td>2.8</td>
<td></td>
</tr>
<tr>
<td>May-08</td>
<td>31</td>
<td></td>
<td>Data not available</td>
<td></td>
</tr>
<tr>
<td>Jun-08</td>
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<td>Data not available</td>
<td></td>
</tr>
<tr>
<td>Jul-08</td>
<td>31</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aug-08</td>
<td>31</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sep-08</td>
<td>30</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oct-08</td>
<td>31</td>
<td>153.4</td>
<td>4.9</td>
<td></td>
</tr>
<tr>
<td>Nov-08</td>
<td>30</td>
<td>191.8</td>
<td>6.4</td>
<td></td>
</tr>
<tr>
<td>Dec-08</td>
<td>31</td>
<td>272.8</td>
<td>8.8</td>
<td>Total in summer = 983.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Avg per day = 8.1</td>
</tr>
<tr>
<td>Jan-09</td>
<td>31</td>
<td>314.5</td>
<td>10.1</td>
<td></td>
</tr>
<tr>
<td>Feb-09</td>
<td>28</td>
<td>200.8</td>
<td>7.2</td>
<td></td>
</tr>
<tr>
<td>Mar-09</td>
<td>31</td>
<td>195.3</td>
<td>6.3</td>
<td></td>
</tr>
<tr>
<td>Apr-09</td>
<td>30</td>
<td>125.9</td>
<td>4.2</td>
<td></td>
</tr>
</tbody>
</table>

The transpiration of willows in the wetland during the summer of 2008 (828.8 mm) was lower than that of summer 2009 (983.4 mm) (Table 6.3). The main reason for this difference was the high levels of solar energy during 2009. The average transpiration of willows was 6.8 mm for the summer period of 2008 and 8.1 mm for 2009. Also, as per the results presented in the Chapter 5, the transpiration of willows was close to twice that of grassland PET for both the study years during summer.

In the present study understorey transpiration was assumed to be minimal and was not included in the evapotranspiration estimation for the wetland water balance.
6.2.1.4 Open water evaporation

The open water area in the wetland was mainly along the stream passing through the wetland. It was filled by unregulated stream flows throughout the year linked to rainfall events. The spatial and temporal variation in the open water area of the wetland stream was estimated based on the water level recorded by the Odyssey™ capacitance probe located in the centre of the wetland and visual recordings of wetland inundated area. The spatial variation of the open water area was mainly linked to the wetland topography and clogging of the stream by the crack willows. The temporal variation (particularly during summer) was linked to the rainfall events. The evaporation rate from the epan under the canopy of wetland crack willow was considered as the open water evaporation rate. Details of methodology followed in estimating the open water and soil evaporation from the wetland has been presented in section 4.2.3 of Chapter 4.
Table 6.4 Comparison of monthly open water evaporation with the transpiration of crack willows

<table>
<thead>
<tr>
<th>Month/Year</th>
<th>No of days</th>
<th>Open water evaporation mm</th>
<th>Summer open water evaporation mm</th>
<th>Transpiration mm</th>
<th>Summer transpiration mm</th>
<th>% of open water evaporation to transpiration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oct-07</td>
<td>31</td>
<td>22.1</td>
<td>155.4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nov-07</td>
<td>30</td>
<td>25.8</td>
<td>201.7</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dec-07</td>
<td>31</td>
<td>14.8</td>
<td>189.1</td>
<td>828.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jan-08</td>
<td>31</td>
<td>12.9</td>
<td>233.6</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Feb-08</td>
<td>29</td>
<td>8.6</td>
<td>228.9</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mar-08</td>
<td>31</td>
<td>7.3</td>
<td>177.2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Apr-08</td>
<td>30</td>
<td>9.2</td>
<td>85.3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>May-08</td>
<td>31</td>
<td>8.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jun-08</td>
<td>30</td>
<td>6.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jul-08</td>
<td>31</td>
<td>7.2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aug-08</td>
<td>31</td>
<td>10.3</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sep-08</td>
<td>30</td>
<td>17.7</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oct-08</td>
<td>31</td>
<td>15.6</td>
<td>153.4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nov-08</td>
<td>30</td>
<td>13.2</td>
<td>191.8</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dec-08</td>
<td>31</td>
<td>13.7</td>
<td>272.8</td>
<td>983.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jan-09</td>
<td>31</td>
<td>17.3</td>
<td>314.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Feb-09</td>
<td>28</td>
<td>12.8</td>
<td>200.8</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mar-09</td>
<td>31</td>
<td>18.8</td>
<td>195.3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Apr-09</td>
<td>30</td>
<td>10.4</td>
<td>125.9</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

On average for both summer periods open water evaporation rate was a meagre 5.8% of crack willow transpiration. The open water evaporation for the summer of 2008 was 43.6 mm (transpiration 828.8 mm) and for 2009 it was 62.6 mm (transpiration 983.4 mm) (Table. 6.4). For the whole study period open water evaporation was 7.7% of willow transpiration. In relative terms open water evaporation was higher during off peak periods (during autumn and spring of low transpiration period) in comparison to transpiration rate. This was mainly due to the low transpiration rate with few leaves on the trees and open water evaporation was mainly driven by supporting meteorological parameters viz., incoming solar radiation and wind speed. Though solar radiation is low during off peak
periods the wind blowing under the willow canopy is able to support open water evaporation.

With open water evaporation from the wetland being less than 6% of transpiration during the summer period, its influence on the total evapotranspiration, and in turn the water balance for the wetland was suggested to be quite low.

6.2.1.5 Soil evaporation

In the present study the exposed soil (wetland area without open water) is wet all year round, and earlier studies of soil evaporation in willow stands and forest floors in New Zealand (Kelliher et al., 1992; Iritz et al., 2001; Barbour et al., 2005) show the conditions are favourable for soil evaporation.

The result of the open water evaporation (epan) for a hypothetical assumption that the whole wetland (16 hectare) is covered in open water was 15.5% of willow tree transpiration for the summer period. Considering soil evaporation at 50% of open water evaporation, it would result in the soil evaporation rate being a maximum of 8% of willow tree transpiration. This shows that the soil evaporation contribution for the total evapotranspiration (transpiration, interception loss, open water evaporation) would be low, and its role in the water balance model was quite low also. In most other studies, under tree canopy soil evaporation was found to be less than 5% (Jones, 1992). In another hypothetical assumption, if soil evaporation of its recognised area was considered to be a maximum that is equivalent to epan evaporation, it would contribute an evaporation loss of 5.3% of the willow transpiration rate. Considering the soil evaporation rate at 50% of open water evaporation would not affect the results greatly but instead provide an approximate input of soil evaporation into water balance approach.
Table 6.5 Comparison of monthly soil water evaporation with transpiration of crack willows

<table>
<thead>
<tr>
<th>Month/Year</th>
<th>No of days</th>
<th>Soil evaporation mm</th>
<th>Summer soil evaporation mm</th>
<th>Transpiration mm</th>
<th>Summer transpiration mm</th>
<th>% of soil evaporation to transpiration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oct-07</td>
<td>31</td>
<td>9.4</td>
<td></td>
<td>155.4</td>
<td></td>
<td>6.0</td>
</tr>
<tr>
<td>Nov-07</td>
<td>30</td>
<td>14.5</td>
<td></td>
<td>201.7</td>
<td></td>
<td>7.2</td>
</tr>
<tr>
<td>Dec-07</td>
<td>31</td>
<td>13.5</td>
<td></td>
<td>189.1</td>
<td></td>
<td>7.1</td>
</tr>
<tr>
<td>Jan-08</td>
<td>31</td>
<td>16.1</td>
<td></td>
<td>233.6</td>
<td></td>
<td>6.9</td>
</tr>
<tr>
<td>Feb-08</td>
<td>29</td>
<td>12.8</td>
<td></td>
<td>228.9</td>
<td></td>
<td>5.6</td>
</tr>
<tr>
<td>Mar-08</td>
<td>31</td>
<td>9.9</td>
<td></td>
<td>177.2</td>
<td></td>
<td>5.6</td>
</tr>
<tr>
<td>Apr-08</td>
<td>30</td>
<td>6.2</td>
<td></td>
<td>85.3</td>
<td></td>
<td>7.2</td>
</tr>
<tr>
<td>May-08</td>
<td>31</td>
<td>4.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jun-08</td>
<td>30</td>
<td>3.2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jul-08</td>
<td>31</td>
<td>2.4</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aug-08</td>
<td>31</td>
<td>4.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sep-08</td>
<td>30</td>
<td>7.2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oct-08</td>
<td>31</td>
<td>7.8</td>
<td></td>
<td>153.4</td>
<td></td>
<td>5.1</td>
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<td>6.4</td>
<td></td>
<td>191.8</td>
<td></td>
<td>3.4</td>
</tr>
<tr>
<td>Dec-08</td>
<td>31</td>
<td>6.7</td>
<td></td>
<td>272.8</td>
<td></td>
<td>2.4</td>
</tr>
<tr>
<td>Jan-09</td>
<td>31</td>
<td>8.6</td>
<td></td>
<td>314.5</td>
<td></td>
<td>2.7</td>
</tr>
<tr>
<td>Feb-09</td>
<td>28</td>
<td>6.4</td>
<td></td>
<td>200.8</td>
<td></td>
<td>3.2</td>
</tr>
<tr>
<td>Mar-09</td>
<td>31</td>
<td>9.0</td>
<td></td>
<td>195.3</td>
<td></td>
<td>4.6</td>
</tr>
<tr>
<td>Apr-09</td>
<td>30</td>
<td>5.2</td>
<td></td>
<td>125.9</td>
<td></td>
<td>4.1</td>
</tr>
</tbody>
</table>

The soil evaporation for the summer of 2008 was estimated at 52.3 mm (transpiration 828.8 mm) and for 2009 it was 30.7 mm (transpiration 983.4 mm) (Table. 6.5). Soil evaporation was more than open water evaporation for 2008 and vice versa for the year 2009 (Table 6.4 and 6.5). This was due to a higher number of rainy days (total rain) during 2009 (compared to 2008), leading to a higher open water area in the wetland and a lower soil area. In 2008 there was a higher soil area and a lower open water area due to fewer rainy-days (compared to 2009). On average for both summer periods the soil evaporation rate was 4.8% of crack willow transpiration. This suggests that the contribution of soil evaporation to total evapotranspiration from the wetland was low (< 4.8%), similar to earlier studies (Jones, 1992).
6.2.1.6 Surface inflow, outflow and storage change

The Waiwhero wetland has few perennial inlets and many small ephemeral inlets providing the inflow. Other than the main ‘inlet’ at the top and ‘outlet’ at the bottom of the wetland there were two other inlets (‘North entry’ and ‘forest’) mainly providing surface water inflow throughout the year (Figure 3.10). The catchment area of the main ‘inlet’ and ‘north’ inlet was mainly covered by pasture, and the ‘forest’ inlet catchment area was covered by *Pinus radiata* plantation. Surface water inflow and outflow from the study wetland was estimated through stream gauging techniques.

As discussed in the time step analysis of water balance data, it was not possible to provide reliable estimates of inflow and outflow for the wetland during high flow periods. Therefore the inflows and outflows are presented for the summer period at daily and monthly intervals. It is important to note that monthly inflow and outflow will not include those days on which flow was affected by rain. The wetland in summer was intermittently inundated with rainfall events during which the wetland soil was wet all around the year.

The monthly inflow and outflow without the inclusion of days affected by rain provide reliable results for the 3 summer months (Jan, Feb and March) in 2008 and the 4 summer months (Jan, Feb, March and April) in 2009 (Table 6.6 and 6.7). Sometimes during the peak summer period the inflow pattern from the ‘inlet’ and ‘north’ passes are irregular for a few days as the water flow through paddocks was blocked at some places for agricultural and domestic usage.

The inflows into the wetland include perennial flows of the main ‘inlet’ at the top of the wetland, and the ‘north’ and ‘forest’ inlets. In Table 6.7, monthly summer period (2008) inflows for each inlet are presented. The volumetric inflow and outflow (l/s) are expressed on in areal basis (mm) assuming the spread of water over the 16 ha wetland. The total number of days the flows were not affected by rainfall was 48 for the summer period of 2008. The main inflow into the wetland during the dry period was ‘inlet’ at the top of the wetland with 36.2 mm for 48 days, which was on average < 0.8 mm/day. During the same period the ‘forest’ and ‘north’ inlets provided inflows of 19.4 mm and 16.2 mm. The total inflow from all the three inlets was 71.7 mm (1.5 mm/day) for the 48 day dry period in
2008. The outflow for the same period was 27.7 mm, on average <0.6 mm/day. The wetland storage loss (change in storage) on average was 3.6 mm/day. In March for the period of 15 days the wetland storage term had increased to 7.1 mm. This was mainly due to a decrease in willow transpiration as the leaves dropped towards the start of winter. The net water loss from the wetland for the 48 days was 217.0 mm (4.5 mm/day).

The pattern for 2008 was the same for the summer period of 2009 (Table 6.7). The total number of days the flows were not affected by rainfall was 51 for the summer period of 2009. The inflow from the main ‘inlet’ was 36.8 mm for 51 days, which was on average, 0.7 mm/day. For the same period the inflow from the ‘forest’ and ‘north’ inlets was 23.5 mm (<0.5 mm/day) and 13.1 mm (<0.3 mm/day) respectively. The total inflow from all three inlets was 73.5 mm (1.4 mm/day) for the 51 day dry period in 2009. However, outflow for the same period was 46.0 mm, on average, 0.9 mm/day. The wetland storage loss on average was 2.5 mm/day. In April for the period of 6 days the wetland storage had increased by 13.5 mm, due to a decrease in willow transpiration. The net water loss from the wetland for the 51 days was 157.2 mm (3.0 mm/day).

The total net loss of water from the wetland was on average 3.7 mm/day for the dry period of years 2008 and 2009 together. This loss could be assigned to groundwater recharge (negative flux) or to evapotranspiration (mainly willow transpiration). This fits with the results of Chapter 5 showing high transpiration from crack willows. Another explanation for the net loss could be sub-surface outflow (interflow). The inflow into the wetland might be flowing out as sub-surface outflow and entering the stream as by-pass flow without being captured at the outflow gauging location. The chance of this occurrence is low due to the geological setting of the study wetland. It is understood that Separation Point Granite occurs roughly somewhere in the middle of the wetland and most of the water infiltrating before this point will move across the catchment to the Moutere valley aquifers and the possibility of sub-surface outflow is low. The objective of the study is to work out these conflicting hypotheses. This inflow loss to the wetland could be better understood in the daily and monthly water balance results presented in the next few sections of the chapter.
Table 6.6 Monthly summer period inflow, outflow and inflow loss for 2008

<table>
<thead>
<tr>
<th>Year 2008</th>
<th>No of days without rainfall</th>
<th>Inflows</th>
<th>Outflow</th>
<th>Storage loss mm</th>
<th>Wetland net water loss mm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Inlet mm</td>
<td>Forest mm</td>
<td>North mm</td>
<td>Total inflow mm</td>
</tr>
<tr>
<td>Jan</td>
<td>11</td>
<td>5.5</td>
<td>6.0</td>
<td>3.6</td>
<td>15.2</td>
</tr>
<tr>
<td>Feb</td>
<td>22</td>
<td>12.7</td>
<td>8.1</td>
<td>2.7</td>
<td>23.6</td>
</tr>
<tr>
<td>March</td>
<td>15</td>
<td>17.9</td>
<td>5.3</td>
<td>9.8</td>
<td>33.0</td>
</tr>
<tr>
<td>Total</td>
<td>48.0</td>
<td>36.2</td>
<td>19.4</td>
<td>16.2</td>
<td>71.7</td>
</tr>
<tr>
<td>Avg monthly</td>
<td>16.0</td>
<td>12.1</td>
<td>6.5</td>
<td>5.4</td>
<td>23.9</td>
</tr>
<tr>
<td>Avg daily</td>
<td></td>
<td>0.8</td>
<td>0.4</td>
<td>0.3</td>
<td>1.5</td>
</tr>
</tbody>
</table>

Table 6.7 Monthly summer period inflow, outflow and inflow loss for 2009

<table>
<thead>
<tr>
<th>Year 2009</th>
<th>No of days without rainfall</th>
<th>Inflows</th>
<th>Outflow</th>
<th>Storage loss mm</th>
<th>Wetland net water loss mm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Inlet mm</td>
<td>Forest mm</td>
<td>North mm</td>
<td>Total inflow mm</td>
</tr>
<tr>
<td>Jan</td>
<td>14</td>
<td>7.9</td>
<td>6.1</td>
<td>1.6</td>
<td>15.6</td>
</tr>
<tr>
<td>Feb</td>
<td>19</td>
<td>10.3</td>
<td>4.9</td>
<td>1.7</td>
<td>17.0</td>
</tr>
<tr>
<td>March</td>
<td>12</td>
<td>12.9</td>
<td>7.2</td>
<td>7.1</td>
<td>27.1</td>
</tr>
<tr>
<td>April</td>
<td>6</td>
<td>5.7</td>
<td>5.3</td>
<td>2.7</td>
<td>13.8</td>
</tr>
<tr>
<td>Total</td>
<td>51.0</td>
<td>36.8</td>
<td>23.5</td>
<td>13.1</td>
<td>73.5</td>
</tr>
<tr>
<td>Avg monthly</td>
<td>12.8</td>
<td>9.2</td>
<td>5.9</td>
<td>3.3</td>
<td>18.4</td>
</tr>
<tr>
<td>Avg daily</td>
<td></td>
<td>0.7</td>
<td>0.5</td>
<td>0.3</td>
<td>1.4</td>
</tr>
</tbody>
</table>
6.2.2 Water balance

The water balance results are presented on a daily basis and then monthly for non-rainy days to average out the outliers and better understand the variations.

6.2.2.1 Daily water balance

The general water balance equation is followed in the present study to estimate the groundwater flux (see equation 2.1).

It was not possible to estimate surface water flows during high flow levels due to site complexity and other logistics. Therefore the daily water balance results are presented for the summer period only. During this period all the components of water balance were estimated or measured as accurately as possible. It is important to note that inputs and outputs during the high flow periods and on rainy days are not accurate in Figure 6.2 to 6.5.

The wetland storage gain (increase in storage) was only on rainy days. However there were also a few occasions during the dry period when water blocked by the farmers in the catchment was released, leading to an increase in storage of the wetland. For the dry periods of 2008 and 2009 the wetland storage loss (due to change in storage) averaged 3.1 mm/day (Table 6.6 and 6.7). The annual average daily transpiration of crack willows in the wetland was (6.4 mm/day). This shows that wetland storage loss was less than the transpiration of willow trees in the wetland. On the other hand all other inputs and outputs in the wetland were quite low. Hence it was interpreted that storage loss from the wetland was from transpiration of willows, without losing out the water from the wetland hydrological system. Therefore, in the water balance equation 2.1 the wetland storage loss was not included into the total outputs to avoid the duplication. However, the wetland storage loss was used in the final estimation of net residual groundwater flux for the wetland.

The daily water balance results for the summer of 2008 showed outputs from the wetland to be higher than inputs (Figure 6.2). In November the wetland showed high outputs compared to inputs. This was due to the contribution of inflows from many other inlets.
around the wetland which were not measured. These small inlets were providing inflows for a few weeks after the winter period and later dried. November was quite dry with no rainy days and therefore the inflow and outflow levels dropped down rapidly. Further, as the days were getting warmer the transpiration of willows (willow Te) increased and contributed around 50% of outputs during November and December. From January, transpiration of willows was on average 7 mm/day and acted as a main contributor to outputs (> 81%). During the period January to March the inputs and outputs from the wetland were quite low. However, during rainy days the inflow and outputs fluctuate rapidly. The major contribution of the output was willow transpiration for most of the non-rainy days from January to March. From mid March, as the leaves from the willows dropped significantly, the transpiration dropped. Later with heavy rainfall towards the end of March both the inputs and outputs from the wetland increased rapidly and on the other hand transpiration of willows dropped down significantly with few leaves on the tree and low energy levels.

![Graph](image)

**Figure 6.2 Daily inputs, outputs, rainfall and transpiration of willow for the summer of 2008**

Inputs = Estimated surface inflows into wetland + precipitation

Outputs = Estimated surface outflow from wetland + willow interception + open water evaporation + soil evaporation + transpiration of willows in the wetland

Note: to provide the figure at higher resolution the inputs and outputs on Y-axis above 40 mm/day around rainy-days are not shown.
Figure 6.3 Daily residual net groundwater flux and rainfall for the summer period of 2008

Net groundwater flux = Inputs – Outputs ± change in wetland storage

Notes:

- Figure at higher resolution shows the net groundwater flux above 40 mm/day and below -10 mm/day on y=axis.
- Negative values (recharge) are in error in the daily water balance estimation due to increase in storage on rainy days and on some occasions it was raining at mid-night.

The estimated residual groundwater flux was reduced by the storage loss in the wetland (change in wetland storage) as it was not included in the outputs of the water balance equation. This provided the net groundwater flux for the wetland hydrological system. The net groundwater daily flux of the water balance results for 2008 showed the wetland as a discharge zone (positive gain into the wetland) (Figure 6.3). However one needs to be aware that high inflows and outflows are not accurate during rainy days. On most occasions immediately after the start of rainfall, inflow shoots up leading to a negative net groundwater flux (recharge). This was due to refilling of the emptied wetland water storage on rainy days and inputs higher than outputs. On some occasions it was raining at

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5 Here after the term ‘net groundwater’ flux means the estimated residual groundwater flux in the water balance equation 2.1 is reduced by the wetland storage loss (change due to storage = Δs). The change in groundwater depth was recorded by the capacitance probe located in the centre of the wetland. The details are provided in the section 4.2.3. Example: If the storage is negative it is summed up with the outputs in the equation of net groundwater flux.
midnight (towards the end of the daily summation), and any outflow increases due to rain were considered in the daily water balance for the next consecutive day. Towards the end of the rainfall event outflow shoots up. The inflow was only measured at three inlets but in reality there were more than 20 inlets (ephemeral) that provided the inflow, thus leading to high outflows compared to inflow towards the end of rainy period. However, within a few days immediately after the rainfall event the inflows for the wetland dropped down to only three measured inlets and all other ephemeral inlets dried out. This shows that the inflows and outflows estimated for non-rainy days were accurate.

The net groundwater flux was estimated based on equation 2.1.

**Net groundwater flux** = Inputs – Outputs ± change in wetland storage

**Inputs** = Estimated surface inflows into wetland + precipitation

**Outputs** = Estimated surface outflow from wetland + willow interception + open water evaporation + soil evaporation + transpiration of willows in the wetland

**Example for January 2008 (Table 6.8)**

**Net groundwater flux (16.8 mm) = inputs (15.2 mm) – outputs (110.5 mm) + change in wetland storage (78.5)**

The daily water balance results for 2009 to a large extent followed the trend to that in 2008, with higher outputs from the wetland compared to inputs. The daily water balance for the summer period for 2009 is provided in Figure 6.4. Unlike the summer period of 2008, there were a large number of rainy days in November and December for the summer period of 2009. Therefore the inputs and outputs from the wetland were quite high until the first week of January 2009. Although the inputs dropped down quickly with warm weather the outputs from the wetland did not drop and stayed high. This was mainly due to inflow from the other non-measured inlets around the wetland. However, from late in the second week of January 2009, the major contributor of outputs was transpiration from willow trees in the wetland. During the first week of February the outflow was almost nil and all the output was evapotranspiration and particularly the transpiration of willows. With the increase in the number of rainy days towards the end of February and early March 2009 the wetland inflow increased slightly. However during non-rainy days between the two rainfall events the major contributor of outputs was still the transpiration of willow trees. From mid March as the leaves from the willows dropped significantly the
transpiration dropped leading to a decrease in outputs. As in 2008, with heavy rainfall during the second week of April, the inflow and outflow from the wetland increased rapidly, while transpiration from willows dropped, with few leaves on the tree and low energy levels.

![Graph](image)

**Figure 6.4** Daily inputs, outputs, rainfall and transpiration of willow for the summer period of 2009

Inputs = Estimated surface inflows into wetland + precipitation

Outputs = Estimated surface outflow from wetland + willow interception + open water evaporation + soil evaporation + transpiration of willows in the wetland

Note: to provide the figure at higher resolution the inputs and outputs on Y-axis above 30 mm/day around rainy-days are not shown.
Figure 6.5 Daily residual net groundwater flux and rainfall for the summer period of 2009

Net groundwater flux = Inputs – Outputs ± change in wetland storage

Notes:
- Figure at higher resolution the net groundwater flux above 40 mm/day and below -20 mm/day on y-axis.
- Negative values (recharge) are error in daily water balance estimation due to increase in storage on rainy days and on some occasions it was rain at mid-night.

The net residual groundwater daily flux in the water balance results for 2009 showed the wetland as a discharge zone (Figure 6.5). The estimated residual groundwater flux was reduced by the storage loss (change in storage) in the wetland as it was not included in the outputs of the water balance equation. As mentioned earlier it needs to be noted that high inflows and outflows were not accurate during rainy days and during high flow periods. During second week of April 2009 there was continuous rain for a few days thus leading to an increase in outputs from the wetland. Negative net groundwater flux (recharge) was in error in the daily water balance estimation due to an increase in the wetland storage on rainy days and on some occasions it was raining at midnight.

6.2.2.2 Water balance for non-rainy consecutive days

The monthly water balance results are provided for non-rainy days in summer excluding days the flow was affected by rainfall. This was done to avoid the unaccounted high flows
on rainy days, and to average out the outliers and better understand the variation. This would help in the quantification of the water balance results for the summer period as opposed to the daily water balance which included rainy days.

The monthly water balance for the summer of 2008 for the total of 48 days is provided in Table 6.8. The inflows and outflows for the month of November, December and April were excluded as they were affected by rain and inflow from the non-measured ephemeral inlets around the wetland. The inputs were on average 1.5 mm/day, outputs 9.0 mm/day and storage loss 3.6 mm/day for the 48 non-rainy days. This showed the net groundwater flux (discharge) into the wetland was 3.9 mm/day. On the other hand the loss through willow transpiration in the wetland was 7.6 mm/day. This suggests that more than 50% transpiration of willows (7.6 mm/day) during the 48 day summer period was supported by net groundwater flux (3.9 mm/day). The outputs without transpiration of willows (1.4 mm/day) were almost equivalent to all inputs (1.5 mm/day). The daily inputs, outputs and transpiration of willows for the non-rainy days included in the monthly summation (Table 6.8) for 2008 are provided in Figure 6.6.

The monthly water balance analysis for the summer of 2009 for the total of 51 days is provided in Table 6.9. The inflows and outflows for the month of November, December and most of the April were excluded as they were affected by rainfall and inflow from the non-measured ephemeral inlets around the wetland. All inputs together were on average 1.4 mm/day and outputs 9.5 mm/day for 51 non-rainy days. The net groundwater flux was 5.6 mm/day and the loss through willow transpiration was 7.8 mm/day. This shows a 70% contribution of net groundwater flux for the transpiration of willows in the wetland. This would need a residual groundwater discharge of 0.3 mm/day even without transpiration of willows, as the total input was 1.4 mm/day and the total output without transpiration of willows was 1.7 mm/day. This clearly shows the wetland as a discharge area (positive flux zone). The daily inputs, outputs and transpiration of willows for the non-rainy days included in the monthly summation (Table 6.9) for 2009 are provided in Figure 6.7.

The monthly water balance results together with the two summer periods for 2008 and 2009 showed outputs from the wetland to be 6.3 times higher than inputs (inflow and direct precipitation). It was understood that net groundwater discharge (groundwater gain)
is 3.3 times the inputs (inflow and direct precipitation) into the wetland, mainly lost through transpiration of willows. This shows that the major contributor of inputs to the wetland was net groundwater discharge. On the other hand the major role in the water balance of the wetland was played by the transpiration of willows, forming 83% contribution of total outputs. Overall this shows the major input into the wetland was net groundwater discharge (groundwater inflow into the wetland) and the major output was transpiration from crack willows.

Additional support for the groundwater discharge into the wetland comes from the water balance, based on inflows, outflows and storage loss (without including the transpiration of willows) (Table 6.6 and 6.7). There was evidence of net wetland water loss for January and February. However, in March 2008 and April 2009, it showed a net wetland water gain of 28.4 mm (15 days period) and 22.7 mm (6 days period) respectively. This change from a loss to a gain in the wetland water the two month period was due to a decrease in transpiration from willow trees in March and April. As the leaves of willows trees dropped with the start of winter, the transpiration rate decreased leading to increased storage and an outflow in the wetland higher than inflows. This provides strong evidence for groundwater inflow (discharge) into the wetland.
Figure 6.6 Daily inputs, outputs and transpiration of willows for non-rainy days included in the monthly summation for 2008

Figure 6.7 Daily inputs, outputs and transpiration of willows for the non-rainy days included in the monthly summation for 2009
Table 6.8 Monthly water balance of groundwater flux and transpiration of willow for the summer period of 2008

<table>
<thead>
<tr>
<th>Months (Year 2008)</th>
<th>Number of days</th>
<th>Inputs mm</th>
<th>Outputs mm</th>
<th>Storage loss mm</th>
<th>Net GW flux mm</th>
<th>Te of willows mm</th>
<th>% contribution of net GW flux to Te of willows</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jan</td>
<td>11</td>
<td>15.2</td>
<td>110.5</td>
<td>78.5</td>
<td>16.8</td>
<td>93.0</td>
<td>0.18</td>
</tr>
<tr>
<td>Feb</td>
<td>22</td>
<td>23.6</td>
<td>212.3</td>
<td>101.7</td>
<td>86.9</td>
<td>184.7</td>
<td>0.47</td>
</tr>
<tr>
<td>March</td>
<td>15</td>
<td>33.0</td>
<td>109.0</td>
<td>-7.1</td>
<td>83.1</td>
<td>87.0</td>
<td>0.96</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>48</strong></td>
<td><strong>71.8</strong></td>
<td><strong>431.9</strong></td>
<td><strong>173</strong></td>
<td><strong>186.9</strong></td>
<td><strong>364.6</strong></td>
<td><strong>--</strong></td>
</tr>
<tr>
<td>Average monthly</td>
<td>16</td>
<td>23.9</td>
<td>144.0</td>
<td>57.7</td>
<td>62.3</td>
<td>121.5</td>
<td>0.54</td>
</tr>
<tr>
<td>Average daily</td>
<td>--</td>
<td>1.5</td>
<td>9.0</td>
<td>3.6</td>
<td>3.9</td>
<td>7.6</td>
<td><strong>--</strong></td>
</tr>
</tbody>
</table>

Table 6.9 Monthly water balance of groundwater discharge and transpiration of willow for the summer period of 2009

<table>
<thead>
<tr>
<th>Year 2009</th>
<th>Number of days</th>
<th>Inputs mm</th>
<th>Outputs mm</th>
<th>Storage loss mm</th>
<th>Net GW flux mm</th>
<th>Te of willows mm</th>
<th>% contribution of net GW flux to Te of willows</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jan</td>
<td>14</td>
<td>15.6</td>
<td>167.2</td>
<td>64.4</td>
<td>87.2</td>
<td>143.8</td>
<td>0.61</td>
</tr>
<tr>
<td>Feb</td>
<td>19</td>
<td>17.1</td>
<td>182.1</td>
<td>63.9</td>
<td>101.1</td>
<td>154.6</td>
<td>0.65</td>
</tr>
<tr>
<td>March</td>
<td>12</td>
<td>27.1</td>
<td>100.2</td>
<td>15</td>
<td>58.1</td>
<td>71.0</td>
<td>0.82</td>
</tr>
<tr>
<td>April</td>
<td>6</td>
<td>13.8</td>
<td>37.5</td>
<td>-13.5</td>
<td>37.3</td>
<td>28.3</td>
<td>1.31</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>51</strong></td>
<td><strong>73.6</strong></td>
<td><strong>487.0</strong></td>
<td><strong>129.8</strong></td>
<td><strong>283.6</strong></td>
<td><strong>397.8</strong></td>
<td><strong>--</strong></td>
</tr>
<tr>
<td>Average monthly</td>
<td>13</td>
<td>18.4</td>
<td>121.8</td>
<td>32.5</td>
<td>70.9</td>
<td>99.5</td>
<td>0.85</td>
</tr>
<tr>
<td>Average daily</td>
<td>--</td>
<td>1.4</td>
<td>9.5</td>
<td>2.5</td>
<td>5.6</td>
<td>7.8</td>
<td><strong>--</strong></td>
</tr>
</tbody>
</table>

Te- transpiration  
GW-groundwater
6.2.3 Groundwater flux

The residual monthly water balance results for the summers of 2008 and 2009 showed the net groundwater flux as discharge (positive gain). The major output was transpiration by willow trees in the wetland. This was opposite to the study hypothesis and showed the wetland as a net groundwater discharge zone, on average 4.8 mm/day, which was providing much of the water supply for the high transpiration of willows (7.7 mm/day) (based on average of Table 6.8 and 6.9). Although the wetland falls within the hypothesized groundwater recharge zone for the Moutere aquifers the results of the present study showed the wetland as a net groundwater discharge zone. This result of the positive net groundwater flux of the Waiherero wetland leads to two questions.

1. Is the net groundwater discharge into the wetland significant?
2. If yes then what are the source(s) of net groundwater discharge into the wetland?

The significance of the net groundwater discharge into the wetland can be understood through error analysis. A full understanding of the possible sources of net groundwater discharge was outside the scope of the present study. However, with the available information of the study and based on earlier hillslope hydrology studies a preliminary attempt to understand the source of groundwater discharge into the wetland was made. This attempt provides insights for future research possibilities in the present study area.

The water balance study does not have accurate estimates of inputs and outputs for the winter period and for rainy days. During these times the water levels in the wetland were quite high and it could be acting as a groundwater recharge zone for the Moutere aquifers located within the hypothesized recharge zone. However, without accurate measurements of inputs and outputs from the wetland during winter it is not possible to provide any findings of net groundwater flux for the winter period. On similar lines there are a large number of studies suggesting that groundwater and surface water interactions in wetlands are highly dynamic, and both temporally and spatially complex due to various hydrogeological, and climatic conditions, catchment land use, and wetland management (Townley and Trefry, 2000; Bullock and Acreman, 2003; McEwan et al., 2006). The
study by Grapes et al. (2006) along the flood plain wetlands of the River Lambourn in central southern England showed much variability in recharge and discharge both in time and space. They noticed spring discharge in the upper catchment with effective recharge taking place exclusively in the winter months, between October and March. Similarly, the vertical movement of ground and soil water in a wetland within a tributary of Red River, North Dakota, USA, reverses several times seasonally (Gerla and Matheney (1996). High evapotranspiration especially in mid-summer as precipitation rates decrease the groundwater discharge into the wetland reverses from groundwater recharge. This could be largely true for the current study but it is difficult to confirm without all inflows and outflows from the wetland being monitored accurately during the high flow season.

6.2.3.1 Error analysis

Water balance studies are useful as they provide a first approximation of inputs and outputs as a basis for hydrologic models and predictions of impact (Winter, 1981; Owen, 1995). The known errors associated with calculating a water balance provide an initial base for further detailed analyses of wetland hydrology. The residual component contains the sum of all errors from the other terms in the water balance approach and therefore one needs to be cautious about the errors. Errors are classified into two categories: measurement errors caused by using imperfect instruments and poor sampling design/incorrect data collection procedures (Winter, 1981), and interpretation errors occurring as a result of using point data in order to estimate quantities for a longer period of time or area. These errors will have a significant effect on the water balance study of wetlands and therefore it is important to include an error analysis in order to allow for realistic use of the water balance results. The error was taken from the literature for each component of the water balance listed in Table 6.10 (Winter, 1981; Owen, 1995). Through cumulative error analysis the residual term groundwater flux is as follows.

Groundwater flux = Inputs – Outputs ± error

The error for the transpiration of willow trees from wetland was estimated through statistical analysis. The nine sample trees used for study of transpiration of wetland was used to estimate the standard error. This provided a sampling error of 20 percent due to
variation of sapflow between individual sample trees. Transpiration of willow trees provides the largest contribution for the total evapotranspiration from wetland and therefore the 20 percent error was considered in the water balance error analysis.

Table 6.10 Error analysis for daily water balance components for the summers of 2008 and 2009

<table>
<thead>
<tr>
<th>Water balance components</th>
<th>Total estimate** mm/day</th>
<th>Error %</th>
<th>Error mm/day</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Inputs</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Surface inflow</td>
<td>1.47</td>
<td>5</td>
<td>0.07</td>
</tr>
<tr>
<td>Direct precipitation on wetland</td>
<td>0.00</td>
<td>5</td>
<td>0.00</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td>10</td>
<td>0.07</td>
</tr>
<tr>
<td><strong>Outputs</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Surface outflow</td>
<td>0.74</td>
<td>5</td>
<td>0.04</td>
</tr>
<tr>
<td>Evapotranspiration*</td>
<td>8.45</td>
<td>20</td>
<td>1.69</td>
</tr>
<tr>
<td>Change in storage</td>
<td>3.07</td>
<td>5</td>
<td>0.15</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td>30</td>
<td>1.88</td>
</tr>
<tr>
<td><strong>Cumulative error</strong></td>
<td></td>
<td></td>
<td>1.95</td>
</tr>
</tbody>
</table>

* Evapotranspiration includes: transpiration by willows (7.7 mm/day) + Open water evaporation (0.37 mm/day) + Soil evaporation (0.38 mm/day) + Interception (0 mm/day) (no interception during non-rainy days)

** Total estimate: It was the average for the summers of 2008 and 2009 without rainy days

The cumulative error for all the water balance components was ±1.95 mm/day. This means the net groundwater discharge of 4.8 mm/day could have an error of ±1.95 mm/day. With the cumulative error added or subtracted the range of groundwater discharge was 2.85 to 6.75 mm/day. Even with all the errors associated in generating the residual term of groundwater discharge into the wetland, it was still a positive flux. As discussed earlier the highest loss for the water balance analysis was transpiration of willows (83% of total outputs). Assuming a 20% error in evapotranspiration measurements, the error equals ±1.69 mm/day.
The major limitation of the residual approach is that the accuracy of the recharge estimate depends on the accuracy with which the other components in the water balance equation are measured or estimated. This limitation would be critical when the magnitude of the recharge rate is small relative to that of the other variables, in particular evapotranspiration and surface runoff, both of which are difficult to measure accurately. Even small inaccuracies would result in large uncertainties of the recharge rates (Scanlon et al., 2002; Ranjan et al., 2006). Therefore it was suggested to measure or estimate all of the components for water balance approach (Owen, 1995). However, in the present study, as the residual value for net groundwater discharge (70% of total inputs) was quite large, the critical limitation of the residual approach being relatively small compared to other variables of the water balance approach would not hold true.

In the present study evapotranspiration is the largest term in the water balance, which is normally true for the summer period due to high incoming solar radiation and other supportive climatological parameters of evapotranspiration (Zhang et al., 2001; Nachabe et al., 2005). It is highly error prone and difficult to estimate accurately as it is an incidental, nonlinear, complex, unsteady process and involves large numbers of climatological, topographical and landuse factors (Moghaddamnia et al., 2009). Therefore a slight error in estimation of evapotranspiration would lead to an erroneous groundwater recharge estimate using the residual approach in the water balance (Diodato and Ceccarelli, 2006). The evapotranspiration process for forested vegetation is complex due to canopy structure, organic floor and root systems forming a complex environment that significantly affects water transfers (Shuttleworth, 1993). Therefore in the present study transpiration of crack willows mainly covering the wetland was estimated through the HPV sap flow technique. It is widely understood that the error in estimation of transpiration for forest stands using the HPV technique is between 5 and 15%, which was included in the error analysis above (Olbrich, 1991; Kostner et al., 1992; Vertessy et al., 1997; Wullschleger et al., 1998). Also the other components of evapotranspiration viz., interception evaporation by the canopy, and soil and open water evaporation were included although they were understood to be low and largely neglected in many studies. However, considering a worst-case scenario evapotranspiration was assumed to be 50% in error (±4.34 mm) and all other components remained with same error percent. This still
showed a net positive groundwater flux (discharge) into the wetland of 0.31 mm/day. This clearly shows that the wetland was a groundwater discharge zone (positive) mainly supporting the high transpiration of crack willows.

6.2.3.2 Source of groundwater discharge to the wetland

Stream flow originates from three different sources or combination thereof: surface runoff; subsurface flow; and groundwater (Whipkey and Kirkby, 1978). One source of supply for stream runoff occurs once the rainfall intensity exceeds the infiltration resulting in overland flow as surface runoff from the catchment. This process is frequently referred to as Hortonian overland flow based on the model developed by Horton (1933), or infiltration excess overland flow. Hillslope hydrologic studies since then have shown that saturated soils in the catchment from rainfall provide overland flow and subsurface flow (lateral flow) (Knisel, 1973; Whipkey and Kirkby, 1978; Anderson and Burt, 1990). This form of surface runoff is frequently referred to as saturation excess overland flow. Most of the earlier studies were done in catchments where the groundwater flux was either very small or absent for most of the year. Later research using isotopic studies in forested, spring-fed swamps in headwater locations showed significant groundwater (shallow and deep aquifers) contribution to the stream runoff (Waddington et al., 1993). In the study of O’Brien (1980) the groundwater contribution dominated storm flow in two New England wetlands located in permanent groundwater discharge areas. Similarly, Bonell et al. (1990) found a significant contribution from shallow groundwater in a valley bottom wetland compared to rainfall event water from saturation overland flow.

Groundwater discharge is mainly controlled by hydro-geomorphology and precipitation patterns in the catchment (Whipkey and Kirkby, 1978; Sklash and Farvolden, 1979; Winter, 1999). A hydrograph curve with a steep slope throughout the stream flow is largely fed by small storage sub-surface flow within the catchment (Weyman, 1973; Whipkey and Kirkby, 1978; Anderson and Kneale, 1982; McGlynn et al., 2002, whereas a hydrograph shaped with a flat slope results from stream flows that were well sustained by groundwater discharges. Also this flat curve was sometimes from large amounts of storage in the upper catchments with large recession curves of low flows (Whipkey and Kirkby, 1978; Sklash and Farvolden, 1979; Turner et al., 1987; Bonell et al., 1990; Buttle and Sami, 1992; Ladouche et al., 2001; Sanderson and Cooper, 2008). Based on the
hydrographs provided in the above mentioned studies the type of hydrograph slopes for the source of water from the sub-surface flow and groundwater source are shown in Figure 6.8.

![Hypothetical recession limb hydrograph curves after rainfall events from various sources to understand the low flows](image)

**Figure 6.8 Hypothetical recession limb hydrograph curves after rainfall events from various sources to understand the low flows**

A study of runoff mechanisms to a wetland from a grassland catchment using isotopic tracers (Bonell et al., 1990) showed the groundwater contribution pattern to the stream flow. They found the groundwater contribution to be more than 60 percent during peak flow periods. Later once the stream flow dropped down to pre-storm levels the isotopic tracers showed the baseflow contribution was all from the groundwater. The flat hydrograph curve of groundwater contribution to stream baseflow is shown in Figure 6.8. Similarly, large numbers of studies showed groundwater contributions of varying levels and periods through isotopic and chemical tracers with flat hydrograph curves after the peak storm flow (Sklash and Farvolden, 1979; Turner et al., 1987; Buttle, 1989; Buttle and Sami, 1992; Ladouche et al., 2001; Sanderson and Cooper, 2008). Roulet (1990) used the hydrometric approach to understand the shallow and deep groundwater discharge for maintenance of wetlands (spring-fed swamps) in Southern Ontario, Canada. He found constant discharge of large groundwater input of greater than 45 mm/day to the wetland. On similar lines many other hydrometric studies showed flat hydrograph curves after the
peak storm flow in wetlands (O'Brien, 1980; Bonell et al., 1990; Buttle and Sami, 1992; Waddington et al., 1993; Hunt et al., 1999). In contrast, the hydrograph slope for subsurface flow with small storage was steep and that of sub surface flow from large storage had comparatively long recession curves with flows continuing for a month or more and could occur without any identifiable groundwater contribution (Whipkey and Kirkby, 1978; Anderson and Kneale, 1982; McGlynn et al., 2002).

Based on the information provided in the above studies the possible sources for groundwater discharge into the wetland could be:

- sub-surface inflow (hillslope discharge) from the local region (surrounding hills)
- contribution from shallow/deep aquifers
- combination of both.

The net residual groundwater discharge slope for the two summer periods was never zero and additionally there was continuous outflow from the wetland. Also the net groundwater flux (discharge) was higher than wetland water storage. With this information and based on the earlier studies discussed above the hypothesis for the net groundwater discharge source for the Waihero wetland was groundwater contribution mainly from shallow and deep aquifers in the region.

A closer look into the daily water balance results between two major rainfall events showed the groundwater flux movement unaffected by rainfall to a large extent. Using this information the groundwater source was predicted based on hill slope hydrology studies discussed earlier.

During both summer periods (2008 and 2009) it was difficult to find long stretches without rainfall events to understand the groundwater flux. However within the available datasets two periods were chosen to understand the groundwater flux between two heavy rainfall events.
As understood in the earlier sections of the chapter the net groundwater flux was mainly positive with groundwater discharge into the wetland. In Figure 6.9 the groundwater discharge dropped down from one day to next and the slope was quite steep immediately after the rainy days. The reason for the sudden drop in the slope on 11/3/08 was due to a small rainfall event in the upper catchments of the wetland on the previous day, increasing the inflow and storage to the wetland. Later, between 17/3/08 and 25/3/08 the discharge would have stabilized around 6 mm/day, if the inflow into the wetland by the farmers in the catchment area was avoided. There are consents given to the farmers in the catchment to store the surface flow water in small dams. Sometimes there was water released into the wetland from these small dams increasing the inflow and the water storage of the wetland. One such incident was between 17/3/08 and 19/3/08. This increased inflow and storage water in the wetland affected the hydrograph of residual net groundwater flux. Without any rainfall event in the wetland/catchment area the net groundwater discharge increased to 0 6 mm/day between 20/3/08 and 24/3/08. Later there was a heavy rainfall event on 27/3/08 which affected the slope of the net groundwater discharge into the wetland.
An important factor that needs to be noted in Figure 6.9 and 6.10 is that high discharge into the wetland on rainy days was in error because the inflows from all the inlets into the wetland were not measured and hence higher than outflow.

![Graph showing net groundwater flux and rainfall](image)

**Figure 6.10** Net groundwater flux (discharge) of the wetland water balance between 20/12/08 and 19/1/09

In Figure 6.10 the groundwater discharge was irregular for first few days mainly affected by rainfall events. After the low rainfall event on first two days of Dec 2008 the slope of the net groundwater discharge hydrograph was quite steep but later stabilized with a flat curve around 14 mm/day between 6/01/09 and 17/01/09. Finally with a heavy down pour on 17/1/09 and 18/1/09 the groundwater flux pattern was disturbed for further understanding of discharge hydrograph.

The net residual groundwater discharge was 14 mm/day (mid January 2009) in Figure 6.10 compared to 6 mm/day (late March 2008) in Figure 6.9, mainly due to high transpiration of willow trees.
Figures 6.9 and 6.10 showed a steep slope of the hydrograph for a few days after heavy rainfall which is believed to be attributed to sub-surface flow (hillslope discharge) from the local region (surrounding hills) as shown in the hypothetical hydrograph curves of Figure 6.8. However, after reaching a certain flow level the discharge hydrograph stabilized with a flat curve which was believed to be continuous groundwater discharge into the wetland with a contribution from shallow and deep aquifers in the region as per the hypothesis (Whipkey and Kirkby, 1978; Sklash and Farvolden, 1979; O'Brien, 1980; Bonell et al., 1990; Buttle and Sami, 1992; Waddington et al., 1993; Hunt et al., 1999; Ladouche et al., 2001). However, it also could be that large storage sub-surface through-flow was contributing to the wetland as the hydrograph curve was not totally flat but dropping slightly for the few consecutive days unaffected by rainfall as shown in Figure 6.8 (Whipkey and Kirkby, 1978; Anderson and Kneale, 1982; McGlynn et al., 2002).

It is important to note that attempts to identify the sources of groundwater discharge into the wetland were based on a water balance that did not specifically cover groundwater inflows. It was not possible to find long periods during which the hydrograph curve was unaffected by rainfall events. Also it is important to be aware that the flow processes are quite complicated with stream flow contributions coming from groundwater ridging, translatory flow, macropore flow and kinematic waves and release of water from surface storage. To pin-point the sources of groundwater discharge into the wetland requires further research with integration of hydrometric methods, groundwater dating and isotopic chemistry.

6.2.4 Role of willow transpiration in the water balance

The wetland water balance for the summers of 2008 and 2009 showed the average daily net groundwater discharge to be 4.8 mm/day, which was close to the average daily transpiration for willows of 7.7 mm/day (Table 6.11). All the outputs without transpiration of willows (1.6 mm/day) were almost equivalent to all inputs (1.5 mm/day). The highest loss in the water balance for the wetland was from transpiration by willows being 83% of total outputs, and similarly, the results of the residual term net groundwater discharge (positive gain) into the wetland was 70% of total inputs. This suggests that the role of transpiration by willows and net groundwater discharge into the wetland was large
compared to inflows, outflow, open water evaporation and soil evaporation. The role of
direct precipitation on the wetland and interception loss was almost nil, as the monthly
water balance analysis was restricted to non-rainy days.

Table 6.11 Average daily transpiration of willow and groundwater discharge during
summer periods (non rainy days)

<table>
<thead>
<tr>
<th>Year (summer period)</th>
<th>Number of days</th>
<th>Inputs mm/day</th>
<th>Outputs mm/day</th>
<th>Storage loss mm/day</th>
<th>Net Groundwater discharge mm/day</th>
<th>Te of willows mm/day</th>
<th>Outputs without Te of willows mm/day*</th>
</tr>
</thead>
<tbody>
<tr>
<td>2008</td>
<td>48</td>
<td>1.5</td>
<td>9.0</td>
<td>3.6</td>
<td>3.9</td>
<td>7.6</td>
<td>1.4</td>
</tr>
<tr>
<td>2009</td>
<td>51</td>
<td>1.4</td>
<td>9.5</td>
<td>2.5</td>
<td>5.6</td>
<td>7.8</td>
<td>1.7</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td>1.5</td>
<td>9.3</td>
<td>3.1</td>
<td>4.8</td>
<td>7.7</td>
<td>1.6</td>
</tr>
</tbody>
</table>

* Outputs without Te of willows = Surface outflow + Open water evaporation + Soil evaporation + Interception (Zero interception during non-rainy days)

It is well understood that groundwater and surface water interactions in wetlands are
mostly controlled by local hydro-geomorphology, climate, catchment land use and
wetland management (Rosenberry and Winter, 1997; Winter, 1999; McEwan et al., 2006).
The long-standing generalization was that wetlands provide groundwater recharge, but in
the last few decades a number of studies have provided results that are contrary to this
generalization (Townley and Trefry, 2000; Bullock and Acreman, 2003; McEwan et al.,
2006). In the present study the wetland was also found to be a discharge zone (positive
groundwater flux), although the wetland falls within the hypothesized groundwater
recharge zone for the Moutere aquifers.

6.2.4.1 Estimation of water outflow from the wetland without willows

The water balance approach shows that the main loss of water through the hydrological
system of the wetland was transpiration of willows (7.7 mm/day) and that all of this was
met through groundwater discharge into the wetland (4.8 mm/day). It would be interesting
to understand the effect of a decrease in transpirational losses through removal of willows
from the wetland. This would lead to significant water savings through the change in land-
use management, and help catchment managers in making more informed water allocation
decisions.
The study considered a hypothetical situation of eradicating all the willows from wetland and assumes that it was filled with open water without any canopy cover. In this regard the open water evaporation rate from wetland was considered equivalent to raised pan open water evaporation at Riwaka climate station (a few kilometres away from study site in Figure 3.1).

The comparison of willow transpiration (7.5 mm/day) with pan evaporation (3.2 mm/day) suggests a 4.3 mm/day decrease in transpirational loss from the wetland during the summer (Table 6.12). This showed pan evaporation was 44% of transpiration of willows and for most of the summer months it was less than 50%. Most of the days were dry in March 2008, and pan evaporation should be high, but for some reason, pan evaporation was < 20% of transpiration of willows and on some days it was zero. This could be due to a malfunctioning of instruments, or an error with the pan evaporation data record. Similarly, comparison of willow transpiration (7.5 mm/day) with PET from grassland (4.3 mm/day) suggests a 3.2 mm/day decrease in transpirational loss from wetland during the summer periods.
<table>
<thead>
<tr>
<th>Month/Year</th>
<th>No of Days</th>
<th>PET mm</th>
<th>PET mm/day</th>
<th>Te of willows mm</th>
<th>Te of willows mm/day</th>
<th>Pan evaporation mm</th>
<th>Pan evaporation mm/day</th>
<th>% of pan evaporation to Te of willows</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oct-07</td>
<td>31</td>
<td>81.5</td>
<td></td>
<td>155.4</td>
<td></td>
<td>84.1</td>
<td></td>
<td>54.1</td>
</tr>
<tr>
<td>Nov-07</td>
<td>30</td>
<td>123.0</td>
<td></td>
<td>201.7</td>
<td></td>
<td>106.2</td>
<td></td>
<td>52.7</td>
</tr>
<tr>
<td>Dec-07</td>
<td>31</td>
<td>110.3</td>
<td>3.6</td>
<td>189.1</td>
<td>6.1</td>
<td>111.0</td>
<td>3.6</td>
<td>58.7</td>
</tr>
<tr>
<td>Jan-08</td>
<td>31</td>
<td>148.9</td>
<td>4.8</td>
<td>233.6</td>
<td>7.5</td>
<td>132.1</td>
<td>4.3</td>
<td>56.6</td>
</tr>
<tr>
<td>Feb-08</td>
<td>29</td>
<td>112.4</td>
<td>3.9</td>
<td>228.9</td>
<td>7.9</td>
<td>93.4</td>
<td>3.2</td>
<td>40.8</td>
</tr>
<tr>
<td>Mar-08</td>
<td>31</td>
<td>82.8</td>
<td>2.7</td>
<td>177.2</td>
<td>5.7</td>
<td>34.8</td>
<td>1.1</td>
<td>19.6</td>
</tr>
<tr>
<td>Apr-08</td>
<td>30</td>
<td>50.7</td>
<td></td>
<td>85.3</td>
<td></td>
<td>39.0</td>
<td></td>
<td>45.7</td>
</tr>
<tr>
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<td>31</td>
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<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
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<td>30</td>
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<td></td>
</tr>
<tr>
<td>Jul-08</td>
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<td></td>
</tr>
<tr>
<td>Oct-08</td>
<td>31</td>
<td>108.7</td>
<td></td>
<td>153.4</td>
<td></td>
<td>79.9</td>
<td></td>
<td>52.1</td>
</tr>
<tr>
<td>Nov-08</td>
<td>30</td>
<td>130.4</td>
<td></td>
<td>191.8</td>
<td></td>
<td>81.4</td>
<td></td>
<td>42.4</td>
</tr>
<tr>
<td>Dec-08</td>
<td>31</td>
<td>168.1</td>
<td>5.4</td>
<td>272.8</td>
<td>8.8</td>
<td>110.2</td>
<td>3.6</td>
<td>40.4</td>
</tr>
<tr>
<td>Jan-09</td>
<td>31</td>
<td>185.9</td>
<td>6.0</td>
<td>314.5</td>
<td>10.1</td>
<td>127.9</td>
<td>4.1</td>
<td>40.7</td>
</tr>
<tr>
<td>Feb-09</td>
<td>28</td>
<td>109.3</td>
<td>3.9</td>
<td>200.8</td>
<td>7.2</td>
<td>91.4</td>
<td>3.3</td>
<td>45.5</td>
</tr>
<tr>
<td>Mar-09</td>
<td>31</td>
<td>118.0</td>
<td>3.8</td>
<td>195.3</td>
<td>6.3</td>
<td>75.8</td>
<td>2.4</td>
<td>38.8</td>
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<tr>
<td>Apr-09</td>
<td>30</td>
<td>67.1</td>
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<td>125.9</td>
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<td></td>
<td>33.8</td>
</tr>
<tr>
<td><strong>Annual daily</strong></td>
<td></td>
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<td></td>
<td><strong>7.5</strong></td>
<td></td>
<td></td>
<td></td>
<td><strong>44.4</strong></td>
</tr>
</tbody>
</table>
Figure 6.11 and 6.12 depict daily comparison for willow transpiration higher than pan evaporation and grassland PET. During October and November the energy levels and willow leaf cover are low compared to the summer months (December, January and February). Therefore the difference between transpiration of willows and pan evaporation was not high, but in the summer months the difference between transpiration of willows and pan evaporation was comparatively high. On the other hand during most part of the study period grassland PET (4.3 mm/day) was slightly higher than pan evaporation (3.2 mm/day).

Considering the hypothetical situation of eradicating all the willows from the wetland and assuming it as an open water wetland, there could be savings of 4.3 mm/day. In the water balance approach for the 16 hectare wetland, 1 mm/day is equivalent to 160000 l/day (160 m³/day). This shows a total water savings of 688000 l/day (688 m³/day or 8 l/s) for a typical summer period between December and March from the 16 hectare wetland. However, with the available information, it is difficult to confirm where this excess water would end up. Considering the wetland falling within the hypothesized groundwater recharge zone for the Moutere aquifers the excess water saved through removal of the willows could recharge the Moutere aquifers. The other possibility of considering the wetland as a groundwater discharge zone, as shown in the earlier sections, is that the excess water would flow through the wetland outlet into the Motueka River.

It is well known that the demand for fresh water during the summer period is quite high in the Moutere region. According to the State of the Environment Report by Tasman District Council the water resources in Moutere Valley are fully allocated in summer and therefore not able to meet the water demands (TDC, 2005). Presently the farming community in the Moutere region is looking at groundwater as a potential resource for intensification of agriculture and for any new area that needs to be brought under cultivation. This clearly shows that water availability has become a particularly important issue in the Moutere valley. Similarly, there is strong evidence of tensions between in-stream users (recreational trout fishery), out-stream users (the farming community) and the local community for water allocation from the Motueka River during low flow periods of summer (Fenemor et al., 2006; Sinner and Fenemor, 2006). Limits are imposed on water
extraction from the Motueka River and further legal proceedings are under way in this regard. This shows in both the situations that the contribution from water savings of 688 m$^3$/day (8 l/s) from a small 16 hectare wetland would be of great value for the water users in the region. However this savings rate, if applied on a large area of crack willow covered wetland, would be quite high.

Figure 6.11 Comparison of daily willow transpiration with pan evaporation and grassland PET for summer 2008

Figure 6.12 Comparison of daily willow transpiration with pan evaporation and grassland PET for summer 2009
6.2.5 Summary

The wetland water balance study was conducted to understand the role of the Waiwhero wetland as a possible recharge area with its location in the recharge zone for Moutere aquifers. The wetland is mainly covered by crack willows, and due to high transpirational losses it could be acting as a discharge zone. The water balance study is an attempt to understand if the wetland is acting as a recharge or discharge (groundwater flux) zone and the effect of transpiration by willows on the net groundwater flux. This study provides more precise information to environmental managers on groundwater gains/losses from the wetland for developing a sustainable management plan.

The groundwater flux was estimated as a “residual” of the water balance equation as it is quite complex to measure directly. The residual estimation of groundwater flux during high flows (winter and during rainy days) was not possible due to inaccurate inflows and outflow measurements from the wetland. Therefore the water balance results are presented for the summer period (December to March) on a monthly basis, and do not include those days on which flow was affected by rain. The approach of using rain-free days is further validated by the fact that transpiration declines during rainy periods (due to a reduction solar radiation and VPD and water covering the leaves) so the influence of the willows on the water balance of the wetland (the focus of this study) would be minimal during rainy periods.

The major components of evapotranspiration for a forested wetland are the sum of transpiration, interception, soil and open water evaporation. The annual average daily transpiration of crack willows was 6.4 mm/day and with a range from 0.8 to 12.4 mm/day. The transpiration of willows was high during summer with high leaf cover compared to other periods. The average daily transpiration of willows was 6.8 mm for the summer of 2008 and 8.1 mm for 2009.

The Waiwhero wetland has three perennial inlets and many small ephemeral inlets providing the inflow. The total number of days when flows were not affected by rainfall was 48 for the summer of 2008, with total inflow from three measured inlets of 71.7 mm (1.5 mm/day) and outflow of 27.7 mm (<0.6 mm/day). This showed that the total inflow of 44.1 mm (0.9 mm/day) was not reaching the outlet. Similarly, in 2009 the total inflow
was 73.5 mm (1.4 mm/day) and the outflow was 46.0 mm (<0.9 mm/day) for 51 days. This showed that the total inflow not reaching the outlet was 27.5 mm (0.5 mm/day) which is around 37% of the total inflow. The inflow loss averaged 0.7 mm/day for the summers of 2008 and 2009. This inflow loss could be groundwater recharge or losses through evapotranspiration.

The residual net groundwater daily flux of the water balance results for 2008 and 2009 showed the wetland as a discharge zone (positive gain). In November the wetland showed that the high outflows were mainly contributed by hillslope groundwater inflow. However, as the days got warmer the transpiration of willows increased, and contributed around 83% of total outputs.

The monthly water balance for the summer of 2008 showed inputs of 1.5 mm/day, outputs of 9.0 mm/day and a storage loss of 3.6 mm/day for 48 non-rainy days. This showed that the net groundwater discharge (positive flux) into the wetland was 3.9 mm/day. On the other hand, the loss through willow transpiration in the wetland was 7.6 mm/day, with total outputs of 9.0 mm/day, whereas all the outputs (1.4 mm/day) without transpiration of willows and storage loss were almost equivalent to all inputs (1.5 mm/day).

The monthly water balance for the summer of 2009 showed inputs of 1.4 mm/day, outputs of 9.5 mm/day and a storage loss of 2.5 mm/day for 51 non-rainy days. This suggests that the groundwater discharge into the wetland was 5.6 mm/day. The transpiration by willows of 7.8 mm/day was close to the groundwater discharge of 5.6 mm/day. The total inputs of 1.4 mm/day were close to total outputs of 1.7 mm/day (without transpiration of willows and storage loss).

Although the wetland falls within the hypothesized groundwater recharge zone for the Moutere aquifers, during summer the wetland forms a groundwater discharge zone. On average for the two summer periods (2008 and 2009) the net groundwater discharge was 4.8 mm/day. It is important to note that the water balance study does not provide information on groundwater flux for winter and rainy days. During these times, the water levels in the wetland were quite high and could be acting as a groundwater recharge zone for the Moutere aquifers being located within the hypothesised recharge zone.
An error analysis showed the significance of the water balance results. With a cumulative error of ±1.95 mm/day the range of groundwater discharge was 2.85 to 6.75 mm/day. Even considering a worst-case scenario and evapotranspiration calculated at 50% in error (±4.34) there is still a net positive groundwater flux (discharge) into the wetland of 0.31 mm/day. This clearly shows that the wetland is a groundwater discharge zone (positive).

A closer look into the daily water balance results between two major rainfall events showed the groundwater flux movement to be unaffected by rainfall. The groundwater discharge dropped down immediately after rain, with a steep slope and the discharge source during the period was believed to be from the surrounding hills. Later the groundwater discharge stabilized around 6 to 14 mm/day and was believed to be a contribution from the shallow and deep aquifers or a combination of local regional inflow and aquifers. It is important to note that attempts to pin-point the sources of groundwater discharge were based on coarse datasets and basic hydrometric field techniques, and therefore the results need to be treated with caution.

Considering a hypothetical situation of eradicating all the willows from wetland and assuming it as open water wetland there could be savings of 4.3 mm/day. It shows a total water savings of 688000 l/day (688 m³/day or 8 l/s) for a typical summer period between December to March from the 16 hectare wetland. This water savings would be of great value for the users in the region during summer and if applied on a large area the savings would be quite high.
CHAPTER 7

7. CONCLUSION

The Waihero wetland, located in the potential recharge area (Rosedale Hills), was hypothesised to be providing groundwater recharge for the Moutere aquifers. Due to intensive agriculture in the region, groundwater abstraction in summer has increased rapidly in the last few decades. This has led to the water resources in the Moutere aquifers being deemed fully allocated for the summer period, and no further water consents from those aquifers are to be approved. In this regard, any new insights into the ground water recharge mechanisms for the Moutere aquifers would help the Tasman District Council in the water allocation process to serve the needs of the farming community in the region. The information may also help in the better management of the recharge zones for sustainable management of those water resources.

Groundwater recharge to the Moutere aquifers from the Rosedale Hills, estimated through earlier catchment water balance studies has been quite low. However, the earlier studies did not include the wetlands located within the Rosedale Hills which could be playing a pivotal role in recharging the aquifers in Moutere region. However, due to the geological setting and the extensive cover of crack willows with their potential for high transpiration losses, the wetland could be acting as a groundwater discharge zone. In this regard, transpiration loss from the crack willows using the sap flow method, and an estimate of the groundwater flux through water balance for the wetland, was conducted.

In the present study the Waihero wetland was hypothesised to be providing groundwater recharge for the Moutere aquifers. The counter hypothesis is that it could be receiving water from groundwater: a groundwater discharge zone. The study results show the wetland as groundwater discharge zone and the hypothesis is not upheld.
7.1. Transpiration of crack willows

The transpiration of the crack willow stand in the wetland was estimated through the HPV sap flow technique. The sap flow rate was scaled up from the sample trees to the stand level based on the tree size dbh determined through a vegetation survey. A non-linear relationship computed between dbh of sample trees (x) and daily sap flow rate (y) showed an $r^2$ value 0.97, representing a strong relationship.

The HPV method of sap flow estimation is based on the integration of a set of point estimates of sap flow velocity in the sapwood of individual trees, and due corrections for the variations of sap flow density were followed at each level. The results of the radial sap flow variability experiment showed the sap flow velocity increased dramatically in newly formed sapwood and then reducing further towards the heartwood. The experiment result of sap flow velocity was close to zero at 98% depth of sapwood, and no sap flow in the heartwood. This showed no sap flow beyond the visible sapwood area. This was re-confirmed through the cut tree experiment in which 97% of sapwood area was stained.

Given the range of uncertainties in the HPV technique the results were validated using the cut tree experiment based on the volumetric measurement of usage of water under field conditions. The average sap flow velocity measured during the experimental period was 1.13 L/hr and evaporation from the pan was 1.21 L/hr. The result of the experiment sap flow measured on the cut tree was 7% less than the pan evaporation. This difference could be due to the cutting of the tree, with some vessels and tracheids getting blocked, and open water evaporation from the measuring container. It could also be due to various experimental errors and have little to do with the HPV technique.

The average sap flux density varied from 68.8 L/m²/h for a 14 cm dbh tree to 237.1 L/m²/h for a 50 cm dbh tree. For a medium-sized tree of 25 cm dbh the average sap flux density was 137.4 L/m²/h. The study of sapwood area and sap flux density on willow species around the world were roughly around the same rates, but the sap flux density for 25 cm dbh willow trees in comparison to other tree species was high.
The average daily transpiration (September to April) of crack willows in the wetland (6.4 mm/day) was close to twice the PET for grassland (3.9 mm/day) based on measurements made approximately 4 km from the study site. The highest willow transpiration rate was 12.4 mm/day and the lowest was 0.8 mm/day. The ratio of annual transpiration of willows to PET was 1.7, but for the summer period it was more than 2.0. Regression analysis showed a strong linear relationship between PET and transpiration ($r^2 = 0.76$).

The transpiration from the willow stand was high during summer and low in autumn and spring. Monthly transpiration was highest in January (315 mm) and February/December (>235 mm). The ratio of transpiration to water equivalent of net radiation on an average from the month of December to March was 1.2. The linear regression relationship between transpiration of willow trees and solar radiation was strong ($r^2 = 0.72$). The lowest transpiration was recorded in April (83 mm) and September (49 mm) and was due to few leaves on willow trees.

A combination of factors affect high transpiration rates in the willow stand compared to short vegetation and open water. High transpiration from crack willows was due to the favourable environmental conditions following the concept of the Soil-Plant-Atmosphere continuum. The meteorological conditions, including the horizontal energy fluxes (advective energy), tree physiological characters and high soil water content are the factors causing high transpiration rates from the willow stand in the wetland.

### 7.2. Wetland groundwater flux

The groundwater flux of the wetland was estimated as a residual in the water balance equation.

The residual estimation of groundwater flux during winter and rainy days was not possible due to inaccurate inflow and outflow measurements from the wetland. Therefore the water balance results are presented only for the summer period (December to March) on a monthly basis. Occasionally, the wetland was inundated by rainfall events during summer, which maintained a high groundwater table. This wetland setting was supposedly encouraging for groundwater recharge from the wetland.
The Waiwhero wetland has three perennial inlets and many small ephemeral inlets providing the inflow. The total number of days when flows were not affected by rainfall was 48 for the summer of 2008, with total inflow from three measured inlets of 71.7 mm (1.5 mm/day) and outflow of 27.7 mm (<0.6 mm/day). This showed that the total inflow of 44.1 mm (0.9 mm/day) was not reaching the outlet. Similarly, in 2009 the total inflow was 73.5 mm (1.4 mm/day) and the outflow was 46.0 mm (<0.9 mm/day) for 51 days. This showed that the total inflow not reaching the outlet was 27.5 mm (0.5 mm/day) which is around 37% of the total inflow. The inflow loss averaged 0.7 mm/day for the summers of 2008 and 2009. This inflow loss could be groundwater recharge or lost through evapotranspiration.

The major components of evapotranspiration for a forested wetland are the sum of transpiration, interception, soil and open water evaporation. The average daily transpiration of willows was 6.8 mm for the summer of 2008 and 8.1 mm for 2009. With interception being nil during non-rainy days, open water evaporation contributed 6% and soil evaporation contributed less than 5% of total evapotranspiration. This showed that the major contributor to evapotranspiration was transpiration from willow trees.

The residual net groundwater daily flux of the water balance results for 2008 and 2009 showed the wetland as a discharge zone (i.e., a positive gain from groundwater). The monthly water balance for the summer of 2008 showed inputs of 1.5 mm/day, outputs of 9.0 mm/day and a storage loss of 3.6 mm/day for 48 non-rainy days. This showed that the net groundwater discharge (positive flux) into the wetland was 3.9 mm/day. The monthly water balance for the summer of 2009 showed inputs of 1.4 mm/day, outputs 9.5 mm/day and a storage loss of 2.5 mm/day for 51 non-rainy days. This suggests that the groundwater discharge into the wetland was 5.6 mm/day.

Although the wetland falls within the hypothesized groundwater recharge zone for the Moutere aquifers, during summer the wetland forms a groundwater discharge zone. On average for the two summer periods (2008 and 2009) the net groundwater discharge was 4.8 mm/day. An error analysis showed the significance of the water balance results. With a cumulative error of ±1.95 mm/day the range of groundwater discharge was 2.85 to 6.75 mm/day. Even considering a worst-case scenario and evapotranspiration calculated at 50%
in error (±4.34) there is still a net positive groundwater flux (discharge) into the wetland of 0.31 mm/day. This clearly shows that the wetland is a groundwater discharge zone (positive).

A closer look into the daily water balance results between two major rainfall events showed the groundwater flux movement to be unaffected by rainfall. The groundwater discharge dropped down immediately after rain, with a steep slope and the discharge source during this period was believed to be from the surrounding hills (hillslope groundwater inflow from small storage). Later the groundwater discharge stabilized at around 6 to 14 mm/day, and was believed to be a contribution from the shallow and deep aquifers or a combination of local region inflow and aquifers.

7.3. Eradicating willows

The water balance approach showed that the main loss of water through the hydrological system of the wetland was transpiration of willows (7.7 mm/day). The extent of water savings estimated for the 16 ha wetland through a hypothetical situation of willow removal, and the assumption that it is filled with open water without any canopy cover, was 688 m³/day or 8 L/s for peak summer period of 3 to 4 months.

The residual water balance of groundwater fluxes for the wetland showed positive gains (groundwater discharge) and therefore it was understood that the excess water would flow into the Motueka River. There is strong evidence of tensions between in-stream users (recreational trout fishery), out-of-stream users (notably the farming community) and the local community for water allocation from the Motueka River during low flow periods in summer. The additional 8 L/s from a small 16 hectare wetland would be of some value for the water users in the region. However this water savings rate if applied to a large area of crack willows would be quite high.

There are large areas of crack willow stands in New Zealand and elsewhere. Today freshwater is a valuable resource for sustainable socio-economic growth of society. Crack willows are known for their physiologically characters and are widely used in restoration/reclamation/management of waterways and wetlands. However, as they have the capability of transpiring large quantities of water they need to be cautiously used and it
is important for water resource policy makers to be aware of their detrimental factors. If there are resources available, it is important for the government to provide incentives through the partial contribution of resources to motivate the community for the removal of willows in areas having serious freshwater availability problems during low flow periods in summer.

7.4. Effect of land-use change on wetland

There are a number of studies supporting clear differences in the mean annual water yield and groundwater recharge under the same soil due to differences in the vegetation canopy type. The water balance studies comparing *Pinus radiata* and pasture both in New Zealand and worldwide have revealed in general that, for a given annual rainfall, pasture catchments yield more stream flow, and groundwater recharge than forested catchments. This is due to the high rainfall losses caused by forest evapotranspiration being a combination of canopy interception and transpiration. Also the longer rooting depth of perennial vegetation decreases the amount of groundwater recharge, as the larger soil moisture deficits developed must be replenished before recharge and sub-surface flow can take place.

7.5. Further research

The water balance study does not have accurate estimates of inputs and outputs for the winter period and for rainy days due to a shortage of resources. During these times the water levels in the wetland were quite high and it could be acting as a groundwater recharge zone for the Moutere aquifers located within the hypothesised recharge zone. However, without accurate measurements of inputs and outputs from the wetland during the winter it is not possible to provide any estimates of net groundwater flux for the winter period. It is well understood that groundwater and surface water interactions in wetlands are highly dynamic, and both temporally and spatially complex, due to various hydrogeological, and climatic conditions, catchment land use, and wetland management. In this regard it is important to conduct further studies to understand the groundwater flux in the wetland during winter period.
It is important to note that attempts to identify the sources of groundwater discharge into the wetland were based on a water balance that did not specifically cover groundwater inflows. To have an improved understanding of the source of groundwater discharge into the wetland it would need an integration of hydrometric methods with groundwater dating and isotopic techniques.

It is well established that the Rosedale Hills area is a recharge area for the aquifers in the Moutere region. The groundwater recharge through earlier water balance studies for small *Pinus radiata* and pasture catchments in the Rosedale Hills showed reduced groundwater recharge in the forested catchment. However an error analysis of the water balance model showed that the low groundwater recharge results could be attributed to errors in estimating evapotranspiration. In this regard it is important to conduct further studies on *Pinus radiata* and pasture catchments in the hypothesized potential recharge areas (Rosedale Hills) for providing accurate estimates of groundwater recharge. This information will help Tasman District Council in the preparation of a Catchment Plan for the better management of the recharge zone for the aquifers in the Moutere valley.

The study of transpiration of crack willows in the wetland showed quite high transpiration rates compared to other tree species. On similar lines it is recommended that studies be undertaken to understand the transpiration rates of other wetland tree species in New Zealand. This information would help agencies decide on the value of introducing different vegetation types in the wetland for better management of the water resources and sustainable ecosystem management.
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APPENDIX 1

Figure A1: Rating curve for inlet low flow

Figure A2: Rating curve for inlet high flow
Figure A3: Rating curve for forest inlet low flow

Figure A4: Rating curve for forest inlet high flow
Figure A5: Rating curve for north entry low flow

Figure A6: Rating curve for north entry high flow
\[ R^2 = 0.98 \]
\[ y = 65.52x^{0.99} \]

*Figure A7: Rating curve for outlet low flow*

\[ R^2 = 0.99 \]
\[ y = 79.08x^{0.25} \]

*Figure A8: Rating curve for outlet high flow*

Note: the above best fit equation was also used to estimate the outflow for stage height above 329 mm, as it was not possible to conduct the stream gauging.