Accounting for water use by willows, wetlands and native riparian plantings

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Executive summary

To help guide policy discussions and manage freshwater resources for optimum outcomes, it is critical for regional councils to have good information on water use. One component that is often overlooked in water use accounting and policy development is the effect of different vegetated land cover in riparian zones and wetlands (e.g., willows versus natives). With the support of Environment Canterbury, Hawke's Bay Regional Council sought an Envirolink Large Advice Grant (HBRC243, MBIE Contract C01X1828) to review the role that riparian vegetation plays in catchment water balances. The questions this study set out to address were:

1. Do willows used for river bank protection consume large amounts of water?
2. Do the evaporative basins of wetlands constructed to treat diffuse source pollution result in water loss from the system?
3. Should consideration be given to balancing increased water use by riparian trees against their ecological benefits, when deciding to plant native vegetation in riparian zones?

The project involved a review of the biophysical properties of riparian vegetation related to water use and modelling of water use under six potential riparian vegetation cover scenarios at a case study site at the confluence of the Tukituki and Waipawa rivers in Hawke's Bay. The vegetation scenarios included:

- Tall willows (20 m canopy height) and trimmed willows (10 m canopy height) used as edge protection;
- Constructed wetlands with and without emergent vegetation (*Typha sp.*) connected to rivers;
- Grass river banks; and
- Water conservative, shallow-rooted native riparian plantings (2 m canopy height).

Water use under each scenario was estimated from a combined Penman-Monteith evaporation and soil water balance approach. Modelling results identified four major factors that control evaporative water loss from the study site:

- Climate – seasonal patterns in climate parameters, including radiation, vapour pressure deficit and water availability, exert tight controls over riparian evapotranspiration. Hence, the answers to the first two questions above are site-dependent. Water losses from tall riparian trees such as willow, and wetlands, are greatest in windy, hot, dry areas.
- The 'soil water deficit effect' – this was a key process influencing riparian evapotranspiration (ET), with the degree of influence dependent on the rooting depth for a given plant species, the depth to groundwater, and the soil water holding capacity at the site. Access to the groundwater table enabled increased plant water use, from the scenarios assessed in this study. This was revealed by the contrasting water use of plants with access to the water table, compared to those without (fig 4-2). Soil water deficit does not constrain water use by plants that maintain access to the groundwater table through summer. Therefore, in seasonally dry settings selecting

plants that can reach the water table (i.e. phreatophytes) is expected to increase water use over selecting plants that cannot. Hence, water savings could be made by planting shallow-rooted species in riparian zones for which transpiration and growth are seasonally limited by water availability. With regard to question 3, above, the benefits of this approach are likely to be greatest in areas set back from water bodies where groundwater is shallow but tall, deep rooted vegetation does not provide ecological benefits important in riverside vegetation (e.g. shading and bank stability).

- Aerodynamic canopy effects – riparian vegetation with tall canopies resulted in greater evaporative water loss than those with short canopies. Hence, water savings could be made by planting shorter plant species in riparian zones. As above, this effort is likely to provide the greatest net ecological benefit in areas set back from water bodies where groundwater is still shallow.
- Stomatal conductance – the degree to which the small pores in plant leaves (stomata) open resulted in noticeable ET differences for riparian vegetation with similar access to water and canopy height. Selection of 'water conservative' riparian species would result in water savings.

Willows provide a good example of vegetation with high access to water, tall canopy and high stomatal conductance. The '20 m willow canopy' land cover had the highest ET of the six riparian cover scenarios modelled.

We identified knowledge gaps around site physical parameters and vegetation parameters that limit our ability to accurately estimate riparian ET and determine the effects of riparian vegetation on stream flow. Aspects of site physical parameters where better knowledge is most needed to improve model confidence are:

- Site-specific estimates of catchment water yield – this requires at a least two-dimensional modelling approach (i.e., including relative areal extent of riparian vegetation covers). A better understanding could be gained by a three-dimensional approach that considers soil processes, including infiltration rates, depth to groundwater and soil moisture distributions.
- Meteorological data from within the riparian area – the nearest meteorological station was located on unirrigated pasture that is unlikely to represent the meteorological conditions at the study site.

Aspects of vegetation ecophysiology most needed to improve model inputs, and hence model confidence, are:

- Maximum leaf area index (LAI) values for riparian plant species across New Zealand - We used the method of Jolly et al. (2005) to calculate the seasonal progression of willow LAI from its seasonal maximum, but seasonal maximum LAI values have not been adequately measured for willow and other riparian species.
- Canopy resistance functions for riparian plant species – Penman-Monteith calculations are particularly sensitive to canopy resistance which is not well characterised for many New Zealand native species.

We see the collection of national datasets of the above two eco-physiological parameters as a useful further step towards the construction of a management tool to quantify water use for different riparian vegetation scenarios. However, we suggest that accurate, site-specific quantification of riparian evapotranspiration would still require considerable site investigation of the physical parameters mentioned above.

1 Introduction

There is increasing pressure on freshwater resources in many parts of New Zealand, and tension between different water users can make policy development and implementation particularly challenging. To help guide policy discussions and manage freshwater resources for optimum outcomes, it is critical for regional councils to have good information on water use. One component that is often overlooked in water 'use' accounting and policy development is the effect of different vegetated land cover in riparian zones (e.g., willows versus natives). Hawke's Bay Regional Council (HBRC), with the support of Environment Canterbury (ECan), sought an Envirolink Large Advice Grant (HBRC243, MBIE Contract C01X1828) to review the role that riparian vegetation plays in catchment water balances. Three specific areas of interest to HBRC and ECan were:

- whether willows used for river bank protection consume large amounts of water;
- whether the evaporative basins of wetlands constructed to treat diffuse source pollution result in water loss from the system; and
- whether consideration should be given to balancing increased evapotranspiration against alongside ecological benefits, when deciding to plant native vegetation in riparian zones.

1.1 Scope

The project involved:

- A review of the biophysical properties of riparian vegetation related to water use, so as to inform water resource managers of the major factors controlling water loss from different riparian vegetation scenarios.
- Using the best available models and local meteorological data to estimate water use arising from six different riparian vegetation scenarios at a case study site at the confluence of the Tukituki and Waipawa rivers in Hawke's Bay. These scenarios include riparian cover of willows, wetlands, and water-conservative native plants.
- Providing brief commentary on gaps in current knowledge and available tools that would improve our ability to model and predict water use in vegetated riparian zones in New Zealand.

1.2 Report outline

This report comprises six sections. In section 2, we provide some background to the issue of water use by riparian vegetation in New Zealand and address key components of water loss from vegetated surfaces, paying attention to the role each parameter plays in evapotranspiration modelling.

In sections 3 and 4, we provide modelling methods and water use estimates, respectively, for six potential riparian vegetation cover scenarios at a case study site at the confluence of the Tukituki and Waipawa rivers in Hawke's Bay. Across the six scenarios there are differences in many of the parameters that influence evapotranspiration (e.g., leaf area, root depth). These scenarios illustrate quantitatively the degree to which differences in these parameters influence evapotranspiration over seasonal cycles. As such, these scenarios can serve to inform riparian management decisions.

Section 5 focuses on information gaps that prevent accurate, site-specific quantification of water use by riparian vegetation in New Zealand. Section 6 comprises a summary and includes recommended areas for further work.

2 Biophysical properties of riparian vegetation related to water use

This section provides background to the issue of water use by riparian vegetation in New Zealand and then reviews key components of water loss from vegetated surfaces. Attention is given to the role each of the following parameters plays in evapotranspiration modelling:

- leaf area index (LAI), including the effect that leaf area has on water loss;
- phenology (cyclic processes, such as seasonal patterns of leaf area);
- leaf-level and canopy level conductance which provide a measure of the degree to which plant species are 'water conservative'; and
- root depth and architecture, including the role root structure plays in gaining access to water.

Finally, we discuss previous studies of vegetation management and removal effects on river flows, with the aim of providing information on which management strategies are likely to work and which will not.

2.1 Background

Evaporative water loss from different vegetated surfaces (e.g., forest, grassland and shrubland) accounts for a large fraction of catchment water balances worldwide (Jasechko et al. 2013, Schlesinger and Jasechko 2014). This is a particularly pertinent issue where decisions regarding vegetation cover drive changes in river flows, as has been reported in many catchments worldwide (Zhang et al. 2001, Doody et al. 2006), and in New Zealand (Fahey and Jackson 1997). Transpiration by riparian vegetation is particularly notable for strong effects on subsurface flows to streams and streamflow, including ephemeral streams (Hall et al. 1998, Cavanaugh et al. 2011). Stream-side trees can consume water from different sources, including soil water, stream water, and groundwater (Dudley et al. 2018). Clearly, the role that riparian vegetation plays in catchment water balances should be considered. However, the potential of riparian vegetation to reduce streamflow may be weighed against the ecosystem services it provides. Riparian areas are hotspots of biodiversity and valuable to preserving surface water quality (Naiman et al. 1993, Boothroyd et al. 2004). Vegetation along riverbanks provides ecological benefits including filtering surface and subsurface water that moves through the soil towards the river channel, maintaining channel water quality by regulating water temperature (through shading), bank stability, turbidity (through root colonisation and surface cover), trapping debris and providing habitat for terrestrial and aquatic organisms; these benefits may vary between vegetation types and species (Sweeney et al. 2004, Scott-Shaw et al. 2017).

An issue frequently raised in New Zealand is whether willows (Salicaceae: *Salix* spp.), a common species in New Zealand's riparian zones, consume large amounts of water relative to other riparian vegetation. Willows have historically been widely selected for river bank protection due to some inherent 'weedy' characteristics, including rapid establishment from stem cuttings, ease of establishment in the presence of grazing livestock (sheep/cows/deer), extensive lateral root development, and tolerance of seasonally wet soils (Wilkinson 1999, Phillips et al. 2014). However, water use by willows is not often accounted for despite the potential to be significant. Potential water savings from riparian willow removal has been reported in specific situations, particularly in Australia (Doody and Benyon 2011, Doody et al. 2014a). Similarly, constructed wetlands and native riparian plantings are being implemented for a variety of beneficial water quality and ecological reasons across New Zealand, without a good understanding of their effects on local water balances.

Sustainable use of water, equitable allocation and protection of water resources requires accurate water balance accounting to advance water saving scenarios. Modern modelling adaptions of methods such as the Penman–Monteith equation (discussed in Section 3) can provide appropriate estimates of riparian water use but are highly dependent on good mathematical representation of some properties of wetlands and other riparian zones. For example, the review of Mohamed et al. (2012) concludes that the Penman–Monteith equation provides an acceptable physical basis for calculation of water use in wetlands but relies on spatially accurate representation of biophysical properties such as the portion of permanent swamps, transpiration properties of vegetation present, and the depth of the water table. Therefore, in Section 2.2 we review the basic principles of the role vegetation plays in local water balances and concentrate our review on the availability of information required to accurately represent riparian zones using Penman-Monteith models.

2.2 Basic principles of riparian evapotranspiration and vegetation effects on local water balances

Evaporation is the processes whereby molecules at the surface of a liquid convert to gas phase. As the temperature of the liquid increases, and molecules near the surface absorb enough energy to overcome the pressure from vapour in the surrounding air, they escape and join the surrounding air in gas phase. Evaporation will not occur if the surrounding air is saturated with vapour. When evaporation occurs, the energy removed from the vaporized liquid reduces the available energy in the liquid, resulting in evaporative cooling. In an enclosed system (e.g. a sealed glass jar half filled with water) liquid will evaporate until the surrounding air is saturated. Hence, the best days for drying washing are when it is warm (plenty of available energy), dry (high vapour pressure deficit (VPD, the difference between the amount of moisture in the air and how much moisture the air can hold when it is saturated)) and windy (allowing water vapour to mix with the atmosphere, increasing the VPD at the boundary between liquid and atmosphere). Lifting washing higher up with a washing line as opposed to lying it on the ground also increases this mixing with the atmosphere. Many of the same processes control rates of transpiration (photosynthetic gas exchange). However, a key difference between transpiration and evaporation is that plants can alter transpiration rates by opening and closing openings on the leaf surface (stomata). The degree to which transpiration of water from the leaf surface is reduced by stomatal closure is termed stomatal conductance (or it's inverse, stomatal resistance). The term 'canopy resistance' incorporates both stomatal conductance at the leaf surface aggregated to the canopy scale, aerodynamic resistance in the canopy, and soil resistance.

Globally, the majority of water lost from the earth's terrestrial surface to the atmosphere occurs during transpiration, rather than evaporation. However, at a local scale rates of open-water evaporation can be significant. The sum of evaporative water loss from the soil surface and from vegetation leaf surfaces via transpiration is known as evapotranspiration (ET).

The term riparian zone refers to the interface between terrestrial and aquatic ecosystems (Figure 2-1). Vegetation within the riparian zone plays a significant role in catchment hydrology due to the close proximity of riparian vegetation rooting systems to water sources that contribute to streamflow. Many species of riparian vegetation can access a range of water sources, including soil water, stream water and groundwater. Evapotranspiration in riparian zones can therefore influence soil moisture, streamflow rates and groundwater levels within a catchment. Temporal and spatial differences in the proportion of water that riparian vegetation transpire from each of these sources can have substantial influences on catchment hydrology (Marttila et al. 2017, Scott-Shaw et al. 2017). In riparian areas vegetation transpiration tends to have particularly large effects on catchment water budgets during low-flow conditions (Davie and Fahey 2005, Marttila et al. 2017). During these dry periods, shallow soils are dry and deeper groundwater tends to contribute a high proportion of streamflow. This deeper water is accessible to deeper-rooted plant species but not shallower rooted plants such as grasses (Dudley et al. 2018). Rates of riparian transpiration and streamflow are therefore dependent on the riparian plant species present, as well as local atmospheric conditions and water supply (Kramer and Boyer 1995).

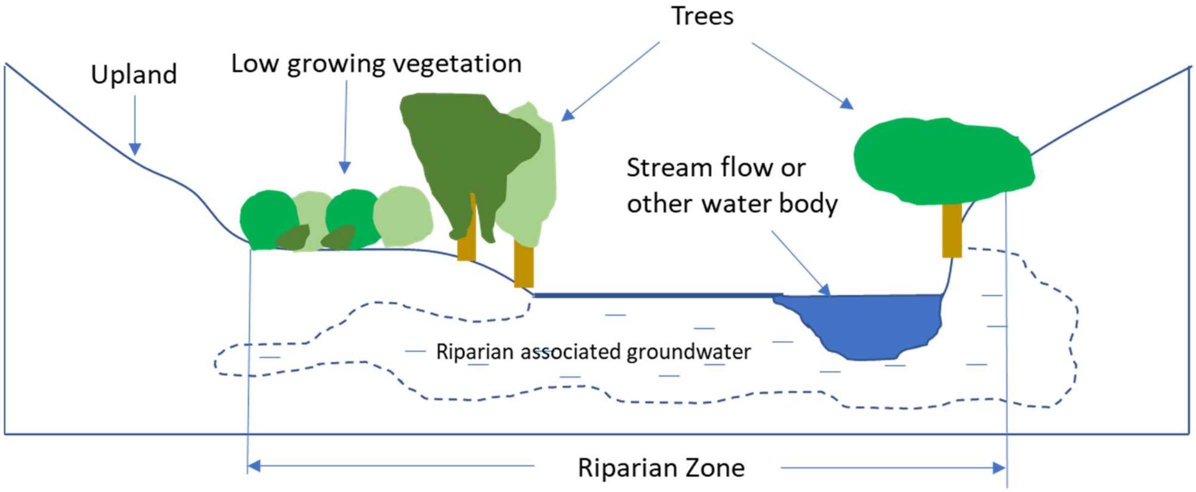

Figure 2-1: Schematic illustration the riparian zone associated with a stream. (Adapted from: United States Department of Agriculture website).

Various process-based ET models have been used to predict water use of riparian vegetation and are frequently used worldwide to estimate ET from native and invasive vegetation types (Doody et al. (2014a) and citations within). The Penman-Monteith model has been used broadly to simulate evapotranspiration rates for various vegetation scenarios (Allen et al. 1998, Theiveyanathan et al. 2004), and specifically for areas with and without willows in Australia and New Zealand (Doody et al. 2006, Marttila et al. 2017) to determine potential water use by willows. The Penman–Monteith model calculates water use by taking into account the effects of climate on trees, including stomatal responses (Theiveyanathan et al. 2004). To run these simulations, data on leaf area index (LAI; maximum and seasonal variation), maximum stomatal conductance and the relationship between stomatal conductance and atmospheric water vapour pressure deficit (VPD) are incorporated (Doody et al. 2006). Model inputs also include site specific climate data including global solar radiation, temperature, humidity and wind speed.

Daily water use can then be predicted based on local weather conditions and resistances to evaporation imposed by the atmosphere (aerodynamic resistance) and tree canopy (canopy resistance) (Doody et al. 2006). Canopy resistance of trees depends on their leaf area (expressed as leaf area index, LAI) and trees moderate environmental drivers of transpiration through opening and closing of stomata. Canopy resistance is therefore also a function of factors that affect stomatal conductance such as radiation, air saturation deficit and soil moisture stress (Doody et al. 2006). The Penman–Monteith equation (Section 4) treats the vegetation canopy as a single ‘big leaf’, where ET is controlled by vegetation stomatal regulation, radiation and airflow (Raupach 1993).Thresholds for reduced transpiration is caused by lower incoming solar radiation, higher air saturation deficit and soil water deficit (via stomatal regulation), and lower LAI. Threshold values for reducing transpiration can typically be: solar radiation of 350 W m^{-2}; saturation deficit of 0.020-0.035 kg kg^{-1} and LAI of 3.0-3.5 (Dunin and Aston 1984, Leuning et al. 1991, Persson 1995, Raupach 1995).

A review paper (Mohamed et al. 2012) analysed the differences between evaporation from wetland surfaces (including a mix of open water evaporation and plant transpiration) compared to evaporation from open water surfaces under the same climatic conditions. Using the Penman–Monteith equation and measurements in selected wetlands around the world, the authors concluded that ET relationships are not generic and are dependent on the biophysical properties of the given wetland surface, the portion of permanent swamps, and the depth of the water table. Therefore, the concept of wetland evaporation being equal to open water evaporation does not hold. Mohamed et al. (2012) suggested that the Penman–Monteith equation provides an acceptable physical basis with which to model wetland ET, but spatially distributed biophysical properties represented as coefficients in this model must be well characterised. Remote sensing data may provide this spatially distributed information. Mohamed et al. (2012) also note that canopy resistance of wetland vegetation appears to have a major influence on Penman–Monteith model results, and canopy resistance is strongly related to the LAI. Information on the spatio-temporal variation of LAI is thus instrumental in calculating the wetland evaporation / open water evaporation ratio. Further, canopy resistance/conductance has also been described as the most sensitive parameter of the Penman–Monteith equation in studies evaluating water use by willows in Australia (Doody et al. 2014a).

Next we describe the information required to accurately represent riparian zones in the Penman-Monteith model, related to transpiration and access to water. This includes: (i) LAI (ii), plant phenology, (iii) canopy/stomatal conductance, and (iv) root depth/architecture/physiology.

2.3 Leaf Area Index (LAI)

Leaf area index (LAI; calculated as leaf area / ground area in m^2 / m^2) is an important structural property of vegetation. Leaf surfaces are the primary border of energy and mass exchange. Processes such as canopy interception, evapotranspiration, and photosynthesis are directly proportional to LAI. Trees with higher LAI therefore tend to transpire at higher rates given similar meteorological, physiological and structural conditions (Vose et al. 2003). Sites with high soil water content typically have highest LAI, although nutrient availability and air temperature are also important in obtaining maximum LAI (Long and Smith 1990, Devakumar et al. 1999, Schaeffer et al. 2000, Gazal et al. 2006).

LAI values for dense willow (*Salix* spp.) stands have been reported as high as 7 (Lindroth et al. 1994, Iritz et al. 2001). More recently, studies in Australia have recorded LAIs for *S. babylonica* and *S. fragilis* in summer of 1.30 and 2.13, respectively. In these studies, a leaf area threshold of 3 was used in the Penman-Monteith model for estimating evapotranspiration from riparian woody vegetation. In the above Australian study of *S. babylonica* and *S. fragilis*, similar ET results to their respective calibrated models were achieved when average LAIs of 1.4 (*S. babylonica*) and 1.5 (*S. fragilis*) replaced the daily (seasonally varying) values determined from field measurement, providing a potential simplification to the Penman–Monteith LAI input parameter (Doody et al. 2014a). It was noted in the Australian studies that the maximum leaf area index of willows in permanently wet parts of creeks was noticeably higher than that of the willows higher up on drier banks (Doody et al. 2014a). In a previous New Zealand study, estimates of LAI were based on the existing model of seasonal LAI for *S. fragilis* in Australia, restricted to the local period in which leaves were present on trees (September 30 to May 30) (Marttila et al. 2017).

For comparison, LAI values for planted crops differ widely but values of 3-5 are common for many mature crops. For a given crop species, green LAI changes throughout the season and normally reaches its maximum before or at flowering. LAI further depends on plant density and the plant variety/ species present (Allen et al. 1998).

We consider that LAI values for willows, and other potential riparian plant species are poorly characterised in New Zealand, relative to their importance for ET modelling. Efficient remote sensing methods have been developed for mapping of willow canopy area through time, enabling accurate scaling of ET for riparian areas. This avenue of research has previously been suggested to improve estimates on the total quantity of water that can be saved by willow removal (Doody et al. 2014a).

2.4 Plant phenology

Transpiration rates are greatly affected by the phenology (i.e., cyclic processes, such as seasonal patterns of leaf area) of the vegetation present, particularly for deciduous trees (Amaravathi 2010). Leaf phenology and its interaction with meteorological parameters plays a major role in the determination of transpiration rates (Kelliher et al. 1992, Schaeffer et al. 2000, Lambs and Muller 2002, Doody et al. 2006, Amaravathi 2010).

Leaf area index (LAI) controls many canopy processes (Savoy and Mackay 2015). The seasonal progression of LAI influences canopy resistance (Sakai et al. 1997, Blanken and Black 2004) and other factors including albedo[1], sensible and latent heat fluxes, CO_2 fluxes, and surface air temperatures (Moore et al. 1996, Randerson et al. 1997, Sakai et al. 1997, Fitzjarrald et al. 2001, Levis and Bonan 2004, Savoy and Mackay 2015). A growing season index (GSI) (Jolly et al. 2005) is an approach that has been used for modelling the seasonality of LAI and is a flexible generalised indicator of phenology. Included in the model are the limitations imposed on plant phenology by temperature, soil water, via its complementarity with atmospheric vapor pressure deficit (VPD), and photoperiod. GSI models the effects of environmental constraints on canopy development and has proven to be useful as a prognostic model of LAI. There is a growing body of literature using GSI as a basis for predicting LAI (e.g., (Zhang et al. 2014, Savoy and Mackay 2015). The model of Savoy and Mackay (2015) has been demonstrated to consistently predict the continuous seasonal progression of LAI.

Despite the importance of LAI in determining transpiration, the phenology of LAI for *Salix* spp. has been relatively poorly characterised in recent studies (e.g., (Doody et al. 2014a, Marttila et al. 2017). A New Zealand study restricted the local period in which leaves were present on willow trees (September 30 to May 30) (Marttila et al. 2017). In Australia, willow LAI declined from a peak in January through to July due to winter senescence and increased from July/August until December. Because phenological processes are tied to environmental conditions such as day length and minimum air temperature, accurate representation of LAI phenology benefits from approaches that can predict LAI for a given species based on local environmental conditions (Jolly et al. 2005, Savoy and Mackay 2015). In Section 4, we incorporate the growing season index (GSI) following Jolly et al. (2005) for seasonal phenology of willows in our simulations for modelling water use of the different vegetation scenarios at the case study site in the Hawke's Bay region.

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[1] A measure of how much light hitting a leaf's surface is reflected without being absorbed.

2.5 Stomatal conductance and canopy resistance

Trees control the influence of the environmental drivers of evapotranspiration by opening and closing their stomata. These environmental drivers include air VPD, soil moisture availability, radiation and LAI. Canopy resistance is therefore a result of the many factors that affect stomatal opening, as well as LAI and aerodynamic resistance (Doody et al. 2006). For example, water stress promotes the synthesis of abscisic acid with subsequent changes in stomatal aperture. Accumulation of abscisic acid in willow leaves and roots has been shown to increase with the duration of water stress, causing decreases in stomatal conductance (Liu et al. 2001). Stomatal resistance (the reciprocal of conductance) has been recorded for *S. babylonica* and *S. fragilis* in Australia, ranging from 4.5 to 871 s m^{-1} and 23 to 909 s m^{-1}, respectively (Doody et al. 2014a). The minimum stomatal resistance values from these ranges were reported as unusually low, compared with typical values of between 100 and 130 s m^{-1} (Mirck and Volk 2009, Aasamaa et al. 2010, Savage and Cavender-Bares 2011). There have been otherwise limited measurements of the maximum stomatal conductance of willows or the relationship between stomatal conductance and atmospheric water VPD (Doody and Benyon 2011), particularly in New Zealand. Studies from the Northern Hemisphere have modelled transpiration of *Salix* (Grip et al. 1989, Lindroth et al. 1994, Persson and Lindroth 1994, Blanken and Rouse 1995, Iritz et al. 2001) however few have validated model results against field observations (Doody et al. 2014a). Considerable genetic variation in water use and growth traits between interbreeding willows has been described (Wikberg and Ögren 2004). Variation is likely to be reflected in stomatal conductance values; modelling of willow transpiration in New Zealand would benefit from measurement of stomatal conductance of local willow varieties under local conditions.

High evapotranspiration is possible with willows because of large stomatal conductances which impose little restriction on evaporative fluxes (Hall et al. 1998). Because willows are most commonly situated where water is readily available near or at the ground surface, these transpiration rates are often not limited by soil moisture deficit (Frédette et al. 2019). However, a European study suggests that these high stomatal conductances are maintained even when there is a large atmospheric humidity deficit and significant soil water deficit (Hall et al. 1998). This study determined that extensive plantings of willow and poplar species will result in reduced drainage to stream flow and aquifer recharge, as well as reduced peak flows. Further the authors suggested that during summer conditions, springs and ephemeral streams may dry up sooner and for longer (Hall et al. 1998).

A second important component of canopy resistance is aerodynamic resistance, which is expected to vary among vegetation types with differing canopy heights. For instance, a papyrus (*Cyperus papyrus*) stand with a height of 4 - 6 m imposes a smaller aerodynamic resistance than a cattail (*Typha* spp.) vegetation of 0.4 - 0.6 m height (Mohamed et al. 2012).

Thus, willow ecophysiology (i.e., high stomatal conductance, tall canopy and high leaf area index), together with their ecological niche, contribute to their high ET rates in wetlands. The high stomatal conductance and willow position in the riparian zone raise concern that large-scale planting of willows may have a negative impact on water resources, through reduced aquifer recharge and river flows. The very high rates of biomass production and productivity common to willow species are tied to these high water-use characteristics; high productivity implies high transpiration rates and therefore water consumption. These traits are shared by poplar species, where high productivity also implies high transpiration rates (Hall, Allen et al. 1998).

Canopy resistance is the most sensitive parameter of the Penman–Monteith equation (Doody et al. 2014a). There is limited useful New Zealand data comparing canopy resistance of *Salix* spp. to other riparian vegetation types in similar situations. Basic knowledge of LAI dynamics and general stomatal conductance for individual species in New Zealand would enable more effective modelling of ET; field measurements are necessary to optimise models.

2.6 Root depth/architecture/physiology

Other aspects of the physical structure of riparian vegetation can influence water balance in catchments. Notably, canopy structure can affect interception (i.e., evaporation of precipitation that falls on plant surfaces directly back to the atmosphere) and root structure determines the soil volume from which plants can potentially draw water (Zhang et al. 2001). Particularly in catchments (and seasons) dominated by sub-surface flows, increases in deep-rooted vegetation tend to result in reductions in catchment discharge (Le Maitre et al. 2000, Dahm et al. 2002).

An expansive, shallow root system is a common feature of *Salix* species (Jackson and Attwood 1996, Li et al. 2006) and likely enables these to trees to tolerate low oxygen in wet/flooded soils. Oxygen levels in such soils can decrease abruptly a short distance below the surface (Armstrong et al. 1976). There are only a few published studies on root system architecture and biomass of willow and native tree species (i.e., other riparian planting options) in New Zealand that allow comparison (Watson et al. 1995, Watson et al. 1999, Marden et al. 2007, Marden et al. 2018). We report these below, with the caveat that the structures of plant root systems are strongly influenced by environmental conditions. For example, where the depth of the water table is within the maximum rooting depth of species, roots of many species will continue to that depth (Rood et al. 2011, Fan et al. 2017). Fan et al. (2017) in a global study combined data from more than 1000 plant species and concluded that groundwater depth represented an important constraint on plant rooting depth. They concluded that the same species experiencing the same climate can produce contrasting rooting depth, depending on water table depth. Shallow groundwater tables push plant roots shallower to avoid oxygen stress, compared to deeper groundwater tables pulling roots deeper to access capillary rise. For example, the shallow rooting of native species observed by Marden et al. (2007), below, was measured in experimental plots with a seasonally-shallow water table.

Studies in Gisborne have shown lateral roots of willows (*Salix matsudana* × *alba* ‘Hiwinui’ and *Salix matsudana* × *alba* ‘Tangoio’) grew 3.9 m (SE 0.6) and up to 9.0 m (SE 0.5) from stems in nine months, with corresponding above ground tree heights of 4 m (SE 0.15) in 9 months; this is at the upper end of growth rates reported internationally. Rooting depths ranged from 0.5 - 0.6 m for ‘Hiwinui’ and ‘Tangoio’, respectively (Phillips et al. 2014). Between 30 and 50% of the total root length was within 1 m of the stem. Roots with diameters up to 5.0 mm accounted for about 75% or more of the total root length, although these roots made up only 20–40% of the total root biomass. More than 90% of the root biomass was contained within half the distance of the maximum lateral extent (5 m) and between 50 and 70% was within 1 m of the stem. Further, willows showed higher levels of above-ground biomass, below-ground biomass and total root length compared to poplars (Phillips et al. 2014). Marden et al. (2007) provided annual (1–5 years) root growth data for 12 indigenous woody species commonly found growing naturally in unstable riparian slope and/or bank environments. The authors suggested that most of the species studied had above- and below-ground growth attributes well suited to colonising steep and unstable riparian slopes where shallow soil failure is prevalent and/or where stream banks are rocky with skeletal soils. All species formed part of early plant succession. Once established, and in the absence of grazing, they were reported as relatively fast growing. The effectiveness of riparian restoration programmes using indigenous species, although potentially high for low-order streams, was reported as being limited by their relatively shallow-rooted habit for bank stabilisation on larger rivers without the prior installation of structural protection works (Marden et al. 2007). Marden et al. (2018) further evaluated the differences in species growth rates for 5-year-old native plantings, including measurements of their allometry (size to shape). This work also examined the influences species mixes and planting densities have on the time required for riparian plantings to become effective in mitigating shallow, storm-initiated landslides. The study provides a description of the root architecture of 12 native early colonising species used in land use conversion and environmental restoration projects. The growth performance of *Coprosma robusta* (karamū), *Plagianthus regius* (ribbonwood), *Sophora tetraptera* (kōwhai), *Pittosporum eugenioides* (lemonwood), *Pittosporum tenuifolium* (kōhūhū), *Hoheria populnea* (lacebark), *Myrsine australis* (māpou), *Pseudopanax arboreus* (fivefinger), *Cordyline australis* (cabbage tree), *Knightia excelsa* (rewarewa), *Leptospermum scoparium* (mānuka), and *Coriaria arborea* (tutu) was measured annually over five consecutive years. Eleven of the species developed a heart-shaped root system, with *Cordyline australis* the only tap-rooted species. By year five, the root/shoot ratio ranged between 0.24 and 0.44, with over 99.5% of the total root mass and root length of all species confined to within 0.5 m of the ground surface and > 73% within 1 radial metre trunk base. The research suggests that the species with the greatest potential for mitigating shallow forms of erosion were: *Pittosporum eugenioides*, *Plagianthus regius*, *Coriaria arborea*, *Pittosporum tenuifolium*, *Hoheria populnea*, *Sophora tetraptera*, and *Cordyline australis* (Marden et al. 2018).

We suggest that field measurements of ET characteristics (LAI and canopy resistance) for these species would enable more-accurate modelling of their water use, including comparison with willows in similar environmental settings. Assessment of maximum rooting depth of willows could be made by studying stem water chemistry (i.e. stable isotope abundance in stem water) across known gradients of groundwater depth (Dudley et al. 2014, Dudley et al. In press).

2.7 Previous studies of vegetation management and removal effects on river flows

Removal of deep-rooted riparian weed species has been identified as a potential strategy for water salvage in areas or seasons where surface soils are dry and subsurface flows dominate (Shafroth et al. 2005, Cleverly et al. 2006, Nagler et al. 2008). Water salvage can be defined as increased water availability (both subsurface and surface waters) for human or environmental beneficial use as a consequence of vegetation and land cover change (Nagler et al. 2010).

In Australia, as in New Zealand, introduced willow species (Salicaceae: *Salix* spp.) inhabit many riparian systems and have been reported to cause various adverse environmental impacts. Of note, high evapotranspiration rates have been observed in willows, particularly those located within stream beds (Doody et al. 2014b). In the Australian context, introduced willows have interspersed with or replaced native vegetation on stream banks. However, there willows also form dense canopies in stream beds while native species do not, so that willow invasion increases total riparian vegetation. Hence, Doody et al. (2014b) suggest that water savings could be achieved by removing willows growing in permanently inundated stream beds. In this case, water savings were calculated as the difference between ET and open-water evaporation. Evapotranspiration of *S. babylonica* over three growing seasons has been reported in Australia with annual mean evapotranspiration of 2,037 mm year^{-1} compared to open water evaporation of 1,491 mm year^{-1} (calculated water saving of +550mm year^{-1}). This compares to *S. fragilis* (over one growing season) with annual mean evapotranspiration of 1,278 mm year^{-1} compared to open water evaporation of 890 mm year^{-1} (calculated water saving of +390mm year^{-1}) (Doody et al. 2014a). Water balance calculations over the three-year period in the Australian study showed that an average potential net water saving of 5.5 ML year^{-1} ha^{-1} of crown projected area was achievable by removing in-stream willows with permanent access to water. Estimated water savings from willow removal varied considerably from year to year at the *S. babylonica* sites as a result of the high interannual variation in willow ET and open-water evaporation, highlighting the importance of deriving estimates of long-term mean willow ET and water savings using long-term climate data. However, this study also observed similar ET rates for native eucalyptus trees and willows growing on stream banks. Therefore, the authors suggest that no net water salvage could be made by replacing streambank willows with native trees. Water salvage feasibility is therefore dependent on the ecohydrological setting in which the non-native trees occur (Doody and Benyon 2011).

A different situation has been reported in a New Zealand study (Marttila et al. 2017), where the current presence of grazing cattle and previous history of vegetation removal in pastoral catchments means that willows also occupy a niche that would be vacant in their absence. Because streamside soils in this situation are seasonally dry and would otherwise be occupied by grasses, water savings would be likely in this situation if willows were removed. However, although the removal of willows would reduce transpiration, shading of streams would be lost and direct evaporation from the water's surface would increase. If willows were replaced with alternative vegetation, transpiration from that replacement vegetation would also need to be accounted for.

Investigations into removal of non-native vegetation to increase water supply were first initiated in the USA in the 1930s based on the perception that large quantities of water could be salvaged for human use. In recent decades, much of this work has focussed on saltcedar (*Tamarix* spp.), a non-native tree which has replaced native riparian species throughout large areas of the southwestern United States (Shafroth et al. 2005). Although some studies (e.g., Owens and Moore (2007)) document riparian transpiration or ET reduction after saltcedar removal, detectable increases in river base flow are not conclusively shown. Further, measurements of riparian vegetation ET in natural settings show saltcedar ET overlaps the range measured for native riparian species, thereby constraining the possibility of water salvage by replacing saltcedar with native vegetation (Doody et al. 2011). Similar findings elsewhere suggest that in general, replacement of weed trees with native tree species will not produce substantial net water savings under co-located conditions (Moore and Heilman 2011, Doody et al. 2014a). In South Africa, the invasion of riparian forests by alien trees has been reported as having the potential to affect the country's limited water resources. Using heat pulse velocity sap flow techniques introduced *Acacia mearnsii* trees used nearly 6 times more water per unit area than the indigenous stand of *Vepris lanceolata* (585 mm a^{-1} compared to 101 mm a^{-1}, respectively). The authors suggest there would be a gain in groundwater recharge and/or streamflow if the alien species are removed from riparian forests and rehabilitated back to a more natural state (Scott-Shaw et al. 2017).

A review and synthesis paper (Salemi et al. 2012) of riparian forest removal and resulting water yields showed riparian forests decrease water yield, however this study did not include willows. Increases in water yield resulting from riparian forest removal were on average 1.32 ± 0.85 mm day^{-1} (483 ± 309 mm yr^{-1}) (n= 9 studies). Similarly, riparian forest plantation or regeneration reduced water yield (on average 1.25 ± 0.34 mm day^{-1} and 456 ± 125 mm yr^{-1}, when prorated to the catchment area subjected to treatment (n= 5 studies)). The authors suggested the tree species present within riparian areas accounted for differences in water yield, and that removing or planting exotic invasive species (e.g., Acacia, Eucalyptus, or Pinus, defined in the study) may cause different changes in yield to planted/regenerated natural vegetation, where native species exhibit lower growth rate, and consequently, lower water-use (Scott et al. 2000, Scott et al. 2004, Salemi et al. 2012). The fore mentioned study also suggests that if riparian vegetation does not root into the stream (and/or groundwater, capillary fringe, etc.), the effect of removing this vegetation on streamflow/groundwater fluctuation during baseflow may be negligible.

An experiment in Nelson, New Zealand (Smith 1992 cited in (Salemi et al. 2012)) attempted to increase nutrient retention in pastoral catchments using forested riparian zones. The study evaluated the consequences of planting pine trees (*Pinus radiata*) within riparian zones (25 to 35 m distance from the stream) on water yield. The 0.5 ha planted area was estimated to be 20% of the total catchment area. The study showed that forest plantation within the riparian area substantially reduced water yield. Annual decreases in streamflow ranged from 52 to 104 mm yr^{-1} over several years. If prorated to the actual planted forest area, the annual decreases were estimated to be 282, 369, 504, and 564 mm yr^{-1} (Smith 1992, Salemi et al. 2012).

The above examples suggest that the potential to save water by removal of invading weed species requires accurate consideration of both the ET of the invading vegetation and also the replacement vegetation and evaporative surface (Doody et al. 2011). In Australia, where willows invaded previously unvegetated stream beds, restoring these areas to open water would reduce ET and therefore potentially increase stream flows. However, willow removal from banks was not considered likely to result in water savings because the resulting vegetation (i.e., the vegetation that replaced the removed willows) showed similar ET characteristics. In the New Zealand example of Marttila et al. (2017), willow replacement with a riparian bank cover of grass only was considered likely to result in water savings because shallow soils in the study area were seasonally very dry. In the USA, *Tamarix* commonly replaces native vegetation with similar ET characteristics, and therefore there is little net change in ET (Doody et al. 2011b).

Pan coefficients (pan factors) using the Penman–Monteith-based method provide a useful tool for estimating evapotranspiration from riparian woody vegetation (Theiveyanathan et al. 2004). The pan coefficients reported by Doody et al. (2014a) are suitable for estimating ET of dense *Salix* stands located in-stream (or along stream edges with an unlimited water supply) but not those situated on stream banks, which may be water limited by seasonal stream contraction or low hydraulic conductivity of the stream banks. Leaf area and canopy resistance in a water-limited environment are likely to be different to those used in the Australian studies to calibrate the Penman–Monteith model. Doody et al. (2014a) suggest that their pan coefficient method is applicable across riparian zones worldwide. We would suggest that the transferability of the method presented by Doody et al. (2014a) could be improved by field-based ET estimates that include local, seasonally dynamic assessments of leaf area index and stomatal conductance; these parameters both highly influence ET calculations and are known to vary based on regional differences in climate.

3 Riparian vegetation scenario modelling

This section outlines the methods for modelling riparian vegetation water use estimates for a study site at the confluence of the Tukituki and Waipawa rivers in the Hawke's Bay. The vegetation scenarios modelled were selected because they are all potential riparian land cover options at the study site. Among the land covers in these scenarios there are differences in many of the parameters that influence evapotranspiration, as described above. It is our intention that these scenarios illustrate quantitatively the degree to which differences in these surface parameters influence evapotranspiration over seasonal cycles. As such, these scenarios can serve to inform riparian management decisions. Because accurate values for many of these surface parameters are not available for the study site (e.g., groundwater access for all vegetation, peak seasonal LAI for willow, and LAI for shallow-rooted native riparian plantings) these are estimated for the various scenarios based on literature values. The model used is 1-dimensional; it does not consider relative areal extent of riparian vegetation cover and does not consider lateral water flows, or distributions of soil processes in space, including infiltration rates, depth to groundwater and soil moisture distributions. Fully quantitative, site specific assessments of differences in flow resulting from these riparian options require detailed site investigations.

Description of the model scenarios are presented in Table 3-1.

Table 3-1: Selected vegetation scenarios for water use model development.

Model No.	Vegetation scenario
1	Large willow (20 m canopy height) used as edge protection along braided rivers
2	Trimmed willow (10 m canopy height) used as edge protection along braided rivers
3	Constructed wetlands without emergent vegetation connected to rivers
4	Constructed wetlands with emergent vegetation (*Typha* sp.) connected to rivers
5	Grass river banks
6	Water conservative, shallow-rooted native riparian plantings along waterways

3.1 General modelling approach

Water use by different vegetation/surface types was estimated from a combined Penman-Monteith evaporation and soil water balance approach adapted from similar soil 'bucket' model approaches. Daily soil water content (S, root zone only) is predicted from the balance of incoming precipitation (P, including irrigation) and outgoing evaporation (E) and drainage (D):

$$S = P - (E_t + E_s + E_i + D) \qquad [1]$$

Where E_t, E_s and E_i are the components of evapotranspiration (ET), including transpiration, soil evaporation and intercepted water, respectively. Each component of ET was treated with separate Penman-Monteith equations (Allen et al. 1998):

$$\lambda E = \frac{\Delta A + \rho_a C_p \frac{(e_s - e_a)}{r_a}}{\Delta + \gamma\left(1 + \frac{r_s}{r_a}\right)} \qquad [2]$$

Where λ is the latent heat of vaporisation, A is energy available for each component (partitioned from net radiation, A_n, to available energy for canopy, A_c, and soil, A_s), Δ is the slope of that saturated vapour pressure curve, γ is the psychrometric constant, ρ_a is the density of air, C_p is the specific heat of air, e_s and e_a are the saturated and actual vapour pressure, r_a is the aerodynamic resistance and r_s is the surface resistance.

Values of A, Δ, ρ_a, e_s and e_a were all calculated from meteorological data according to Allen et al. (1998), using measurements from NIWA's climate station at Waipawa (39.9416°S; 176.5896°E) in the Hawke's Bay Region. The station records hourly global radiation, air temperature, relative humidity, and wind speed at 2 m height, as well as incoming precipitation. Partitioning of (A_n) amongst plant (A_c) and soil (A_s) was a function of leaf area index (LAI) and a Beer-Lambert light extinction coefficient, *k*, which was set to 0.5 (Graham et al. 2016). In this case, since E_t and E_i use a similar energy source and are subject to similar canopy aerodynamic effects, E_i was not modelled independently, but was assumed to be part of E_t.

Aerodynamic resistance at the plant canopy height was estimated as (Allen et al. 1998):

$$r_a = \frac{\ln\left(\frac{z-d}{z_{om}}\right) * \ln\left(\frac{z-d}{z_{oh}}\right)}{K^2 * u} \qquad [3]$$

Where z is the height of meteorological measurements, d is the zero-plane displacement height (2/3 canopy height), K is the von Karman constant, u is the wind speed, and z_{oh} and z_{om} are the roughness coefficients for heat and momentum, respectively. For calculation of E_s, r_a at the soil level is taken as five times that calculated for the canopy height (Kirschbaum 1999). Since climate measurements were taken at 2 m height above a grass canopy, it was necessary to assume that measured wind speed represented that 2 m above the canopy for tall vegetation types as well.

Surface resistance is determined by both the component being modelled (E_s or E_t) and responses to environmental drivers. In the case of the canopy, r_s is represented by:

$$r_{s,c} = \frac{r_{c,min}}{\min\left(1,\frac{S}{S}*\right)*\min\left(1,\frac{LAI}{LAIcrit}\right)*\min\left(1,\frac{Tmin}{Tcrit}\right)*\min\left(1,\frac{\mathrm{I}}{\mathrm{Icrit}}\right)*(1-\frac{\mathrm{VPD}}{\mathrm{VPDcrit}})} \qquad [4]$$

Where $r_{c,min}$ is the minimum canopy conductance, S^* is the critical threshold for root water uptake, and T_{crit}, VPD_{crit}, LAI_{crit}, and I_{crit} are thresholds values for temperature, VPD, LAI, and irradiance respectively. Critical values for willow were taken from Doody et al. (2006). Values of S^* were broadly assigned a value of 0.4 for woody species and 0.5 for herbaceous species to represent greater access to deep water sources by woody species.

In the case of soil surface resistance, r_s is represented by:

$$r_{s,s} = \frac{r_{s,min}}{\min(1,\ S/S_b)} \qquad [5]$$

Where $r_{s,min}$ is the minimum soil resistance and S_b is the volume of water in the soil at saturation. Values of $rs_{,min}$ for bare soil were taken from van de Griend and Owe (1994).

For this study, we assumed that the volume of soil water at saturation was 150 mm in all six riparian vegetation scenarios we modelled. Willows could use water from the soil but were unconstrained once it reached zero. For the simulation of *Typha* spp., both E_s and E_t were unconstrained by soil water.

Seasonal phenology of willow was simulated using the method of Jolly et al. (2005).

3.2 Assumptions

We made a number of assumptions and simplifications in our approach to estimating vegetation water use at the study site. Primarily, we adapted the well-used FAO-56 version of the Penman-Monteith model, which has been developed and tested for uniform crop systems, to the heterogeneous riparian environment. An important contrast between willows and open water or grass systems is the aerodynamic effect of increased canopy height and roughness. Our calculations of r_a with fixed relationships to canopy height, used in Allen et al. (1998), likely do not precisely capture the complexity and seasonality of aerodynamic resistance in riparian willows.

We used climate data from Waipawa; the nearest NIWA climate station to the study site (located ~ 5 km northwest). Climate data were available from 27/06/2007 to 8/02/2019 Climate measurements at this site are taken at 2 m height, typically over an unirrigated grassland. Use of these measurement data for modelling wetland evaporation is problematic. There is a strong interaction between the land surface and near surface climate. In particular, conditions of vapour pressure deficit (VPD) may differ strongly between a water limited grassland and wetland ecosystem. We also made the assumption that these measurements were representative of the temperature, VPD and wind speed conditions 2 m above the canopy when simulating taller vegetation. We recognise this had the potential to introduce significant uncertainty into our results and that air temperature, humidity and wind speed typically exhibit vertical gradients.

We took a deterministic approach to modelling the different vegetation types. All values of LAI, seasonal phenology, and r_s were selected from within a range of literature values, not specific to the conditions of Hawke’s Bay, or New Zealand. Likewise, values of S_b and S* were all approximated. Thus, the results depend strongly on the quality of these available approximations.

3.3 Riparian scenarios

3.3.1 Data sources for all models

Parameters used in the water balance models to represent each riparian vegetation/surface scenario are provided in Table 3-2. The source(s) of these parameters and the rationale for their selection are given in the subsequent sections.

3.3.2 Model 1: Large willow (20 m canopy height) used as edge protection along braided rivers

Canopy height for this model was set at 20 m as specified in the project scope. Willows have large, spreading canopies reaching heights of ca. 20 m leading to large aerodynamic effects on canopy resistance. LAI was modelled for the site location following the methodology of Jolly et al. (2005), using the NIWA climate station data at Waipawa, with a maximum summertime LAI of 3 based on previous studies of *Salix fragilis* in New Zealand and Australia (Doody et al. 2006, Marttila et al. 2017). Values for minimum canopy and soil resistances follow values from Doody et al. (2006) and van de Griend and Owe (1994) respectively as detailed in Section 4. Groundwater access is assumed for all willows in the riparian zone, with the effect in the model that drying of surface soils does not restrict willow transpiration (Johnston et al. 2011). Critical values for VPD, LAI and irradiance are taken from Doody et al. (2006).

Table 3-2: Parameters used in the water balance model for representing each vegetation/surface type1.

Model No.	Scenario	Canopy height (m)	LAI	$Rc_{,min}$ (s m^{-1})	$Rs_{,min}$ (s m^{-1})	Ground water access?	Standing water?	S*	T_{crit} (°C)	VPD_{crit} (kPa)	LAI_{crit}	I_{crit} (MJ m^{-2})
1	Willow spp.	20	3*	36	10	Yes	No	-	5	3.2	3	30.24
2	Willow spp.	10	3*	36	10	Yes	No	-	5	3.2	3	30.24
3	Grass	0.12	3	58	10	No	No	0.5	5	-	-	-
4	Typha	2	3	100	100	Yes	Yes	-	5	-	-	-
5	Other	2	3	120	10	No	No	0.4	5	-	-	-
6	Open water**	-	-	-	-	-	Yes	-	-	-	-	-

[1] Abbreviations are given for leaf area index (LAI), minimum canopy ($Rc_{,min}$) and soil ($Rs_{,min}$) resistances, critical values for root water uptake (S*), temperature (T_{crit}), vapor pressure deficit (VPD_{crit}), LAI (LAI_{crit}), and irradiance (I_{crit}) and whether or not the vegetation has access to ground/stream water or presence of standing water for wetlands. Note: Model 6 –'Constructed wetlands without emergent vegetation connected to rivers' – uses the Penman open water evaporation model which does not have canopy resistance functions but instead has an empirically-derived aerodynamic component.

* Seasonality simulated according to Jolly et al. (2005).

** Representing constructed wetlands without emergent vegetation.

3.3.3 Model 2: Trimmed willow (10 m canopy height) used as edge protection along braided rivers

Canopy height for this model was set at 10 m, as specified in the project scope, to determine the water savings that could be gained by maintaining a shorter willow canopy, thereby reducing aerodynamic effects on canopy resistance. All other parameters follow those described for model 1.

3.3.4 Model 3: Grass river banks

ET of well-watered grass is relatively well understood and can be accurately modelled using the FAO-56 approach. In this riparian vegetation scenario, we assumed that grasses on the bank do not have access to the stream water and are thus constrained by soil water availability. Canopy height for this model was set at -0.12 m, following the FAO-56 approach. LAI was set at 3 without a seasonal cycle, a median value for grassland worldwide (Korte et al. 1982). Values for minimum canopy resistance were set at 58 s/m according to a global synthesis of grassland canopy resistance (Kelliher et al. 1995), and soil resistance follows values from van de Griend and Owe (1994). We assumed that grasses could not access groundwater, and that transpiration becomes restricted below a threshold value for soil water content of 0.5, with the effect in the model that drying of surface soils below 50% of their water holding capacity begins to restrict transpiration. No critical values were assigned for LAI and irradiation because ET of low vegetation is typically more coupled to incoming radiation while large trees exert greater stomatal control (Jarvis and McNaughton 1986).

3.3.5 Model 4: Constructed wetlands with emergent vegetation (*Typha* sp.) connected to rivers

We assumed this riparian vegetation scenario should reflect conditions in natural *Typha* wetlands. Based on this assumption, canopy height for this model was set at 2 m and LAI was set at 3 without a seasonal cycle. Values for minimum canopy and soil resistances were set to a static value of 100 based on Goulden et al. (2011) who conducted eddy covariance measurements in a Californian *Typha* marsh. Groundwater access was assumed, with the effect in the model that drying of surface soils does not restrict transpiration. In natural *Typha* wetlands the area below the canopy is typically inundated with a litter layer over water so we applied an understory (ground) resistance value of 100, also following Goulden et al. (2011).

3.3.6 Model 5: Water conservative, shallow-rooted native riparian plantings along waterways

For this riparian vegetation scenario we estimated physical and ecohydrological characteristics of a hypothetical water-conservative native shrub species. Canopy height for this model was set at 2 m. LAI was set at 3 without a seasonal cycle. Values for minimum canopy resistances were set at a relatively high value of 120 s/m to represent a water-conservative trait while soil resistances followed values from van de Griend and Owe (1994). Access to groundwater was not assumed, and transpiration becomes restricted below a threshold value for soil water content of 0.4, with the effect in the model that drying of surface soils is slower to restrict transpiration compared to grass. No critical values were assigned for LAI and irradiation for the same reason as none were assigned in Model 3.

3.3.7 Model 6: Constructed wetlands without emergent vegetation connected to rivers

This model represents conditions for a wetland adjacent to the stream with no emergent vegetation. We treated this situation as standing (open) water without vegetation cover and used the Penman open water evaporation model, rather than the Penman-Monteith model used for the other riparian vegetation scenarios. The open water evaporation model does not have canopy resistance functions but instead has an empirically-derived aerodynamic component, so that many of the parameters listed for other scenarios are absent for this scenario.

4 Riparian vegetation scenario modelling results

In this section we provide the key results from modelling water use of each of the six distinct riparian vegetation scenarios described in Section 4.3. We modelled an ~11-year period from June 2007 to February 2019, this period being limited only by the availability of suitable climate data.

4.1 Key patterns

Seasonal pattern of ET resembles that of climatic drivers, primarily incoming radiation (Rg), temperature (T) and vapor pressure deficit (VPD, Figure 4-1). While LAI is also an important determinant of transpiration, limitation of transpiration by low leaf area can be offset by enhanced radiation interception by the soil surface, and thus soil evaporation, when soil water is non-limiting (Graham et al. 2016).

Between April and September at the Hawke's Bay study site, precipitation is typically sufficient to fulfil demand for ET (Table 4-1). However, from October to March, potential ET exceeds precipitation and water availability in the soil can substantially limit ET for vegetation without access to stream water (Figure. 4-2, Table 4-2). As a result, simulations for riparian vegetation scenarios which do not access stream water (grass, other shallow-rooted water conservative species) indicate ET is substantially lower during these months.

Secondary to the effect of seasonal soil water availability is the surface resistance (including canopy and aerodynamic resistance) of the respective vegetation types. Taller vegetation has a higher surface roughness and reduced aerodynamic resistance to water vapour exchange. Likewise, high canopy conductance (the aggregate of stomatal conductance) can enhance ET.

Table 4-1: Mean monthly precipitation at the Hawke's Bay study site. Calculated evaporation from a well-watered reference crop (ETo) as estimated from Allen et al. (1998) over the 11-year simulation period. The latter calculation uses climate data from NIWA's climate station at Waipawa (39.9416°S; 176.5896°E).

Month	Precipitation (mm)	ETo (mm)
Jan	60 ± 17	151 ± 4
Feb	34 ± 7	114 ± 4
Mar	56 ± 11	94 ± 2
Apr	79 ± 18	62 ± 2
May	70 ± 13	44 ± 2
Jun	76 ± 11	30 ± 1
Jul	98 ± 17	36 ± 2
Aug	69 ± 8	48 ± 1
Sep	78 ± 16	70 ± 2
Oct	56 ± 11	100 ± 3
Nov	37 ± 10	122 ± 3

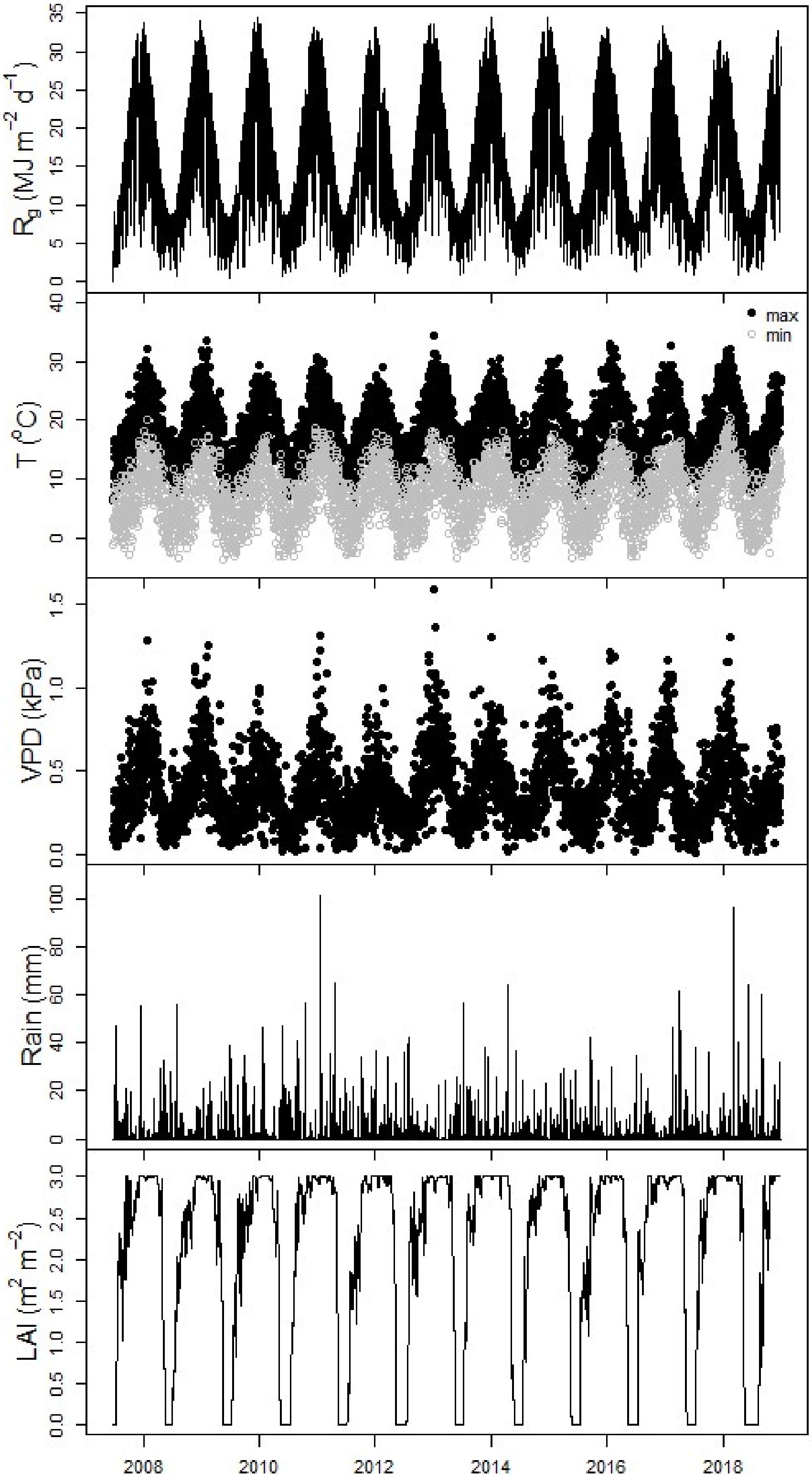

Figure 4-1: Time-series of daily climate drivers measured at NIWA's climate station at Waipawa (39.9416°S; 176.5896°E) in Hawke's Bay. Shown (from top to bottom) are global radiation (Rg), air temperature (T), vapour pressure deficit (VPD), rainfall, and predicted leaf area index (LAI) for deciduous species (willow only).

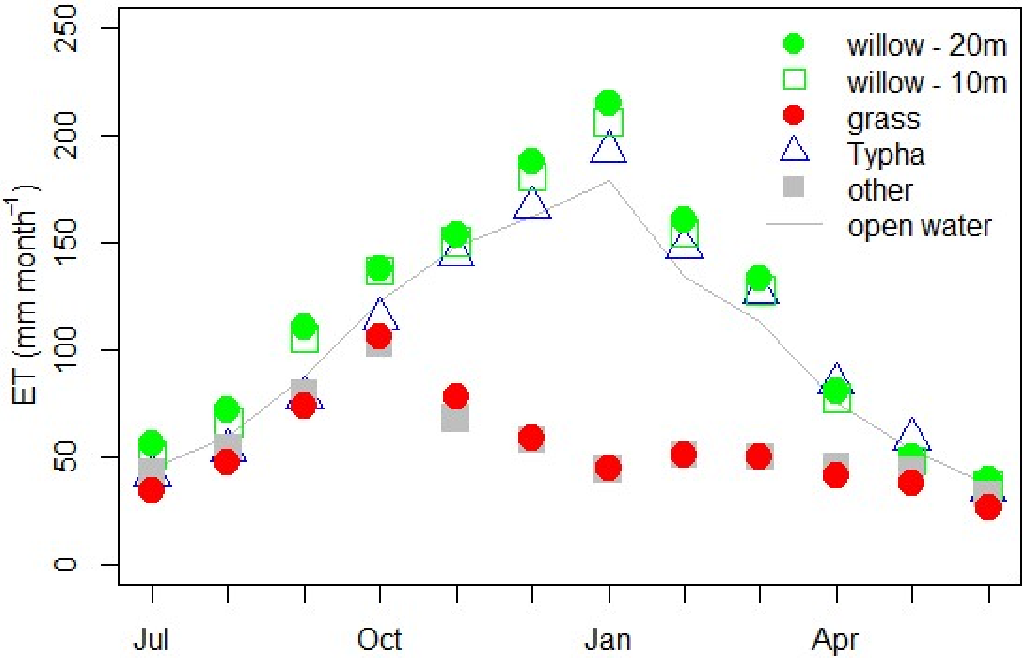

Figure 4-2: Monthly mean ET for the six riparian vegetation cover scenarios over the 11-year model simulation. Included are 20 m willow, 10 m willow, seasonally dry grass, constructed wetland with emergent vegetation (Typha), a hypothetical water-conservative shrub species (other) and an open water wetland with no emergent vegetation (open water).

Table 4-2: Mean monthly evapotranspiration (ET, mm) for six riparian vegetation scenarios over the 11-year model simulation. Error bars (± SEM) indicate variability in ET related to climate drivers and not true model uncertainty.

Month	Willow 20 m	Willow 10 m	Grass	Typha	Other	Open water
Jan	215 ± 6	206 ± 5	44 ± 8	193 ± 7	44 ± 8	179 ± 5
Feb	161 ± 6	154 ± 6	50 ± 11	147 ± 6	51 ± 11	134 ± 4
Mar	133 ± 4	127 ± 4	49 ± 6	126 ± 5	50 ± 6	113 ± 3
Apr	80 ± 5	77 ± 4	41 ± 6	84 ± 3	45 ± 7	75 ± 2
May	50 ± 4	48 ± 3	37 ± 3	58 ± 5	43 ± 4	53 ± 2
Jun	39 ± 3	36 ± 2	26 ± 2	34 ± 2	32 ± 2	37 ± 1
Jul	56 ± 4	50 ± 3	34 ± 3	41 ± 4	43 ± 4	44 ± 2
Aug	72 ± 4	66 ± 4	47 ± 2	53 ± 2	54 ± 3	59 ± 1
Sep	111 ± 8	105 ± 7	73 ± 3	78 ± 4	79 ± 4	87 ± 3
Oct	137 ± 6	137 ± 6	106 ± 3	115 ± 5	103 ± 5	123 ± 3
Nov	154 ± 5	150 ± 5	77 ± 11	144 ± 5	68 ± 12	148 ± 4
Dec	188 ± 7	181 ± 7	59 ± 12	166 ± 6	57 ± 12	162 ± 5

Table 4-3: Annual evapotranspiration (mm) for the six riparian vegetation scenarios over the 11-year simulation period.

Year	Willow 20 m	Willow 10 m	Grass	*Typha*	Other	Open water
2008	1406	1342	510	1294	538	1260
2009	1387	1331	658	1217	691	1220
2010	1393	1329	698	1189	724	1192
2011	1409	1343	795	1170	829	1177
2012	1275	1228	638	1127	663	1167
2013	1557	1485	675	1350	694	1281
2014	1374	1329	601	1263	602	1238
2015	1421	1369	599	1263	639	1243
2016	1364	1312	543	1343	549	1254
2017	1419	1356	634	1231	653	1193
2018	1345	1287	744	1188	781	1144
Median	**1393**	**1331**	**638**	**1231**	**663**	**1220**

4.2 Individual scenario results

Evapotranspiration (ET) results for each riparian vegetation scenario are described below against ET for a well-watered reference grass crop (ETo). This calculated evaporation from a well-watered reference crop (ETo) as estimated from Allen et al. (1998) is used for comparison because it is well-studied internationally and likely to be both accurate and representative of irrigated grasslands near the site.

4.2.1 Model 1: Large willow (20 m canopy height) used as edge protection along braided rivers

Willow was modelled as having permanent access to stream water, thus transpiration was never limited by water availability. In addition, the tall canopy resulted in an aerodynamic resistance which was 12% of that calculated for a reference grass surface at the mean wind speed of 1.9 m/s. This combined with a low canopy resistance resulted in a calculated annual ET which exceeded ETo by 38% and exceeded open water evaporation by 15% (Table 4-3).

4.2.2 Model 2: Trimmed willow (10 m canopy height) used as edge protection along braided rivers

Trimmed willow was simulated as identical to the tall willow, although with a shorter (10 m) canopy height. As a result, canopy resistance was slightly lower than for the 20 m willow scenario. This difference was relatively minor compared to differences between willow and some other riparian covers. ET for 10 m willow canopy was 10% larger than open water evaporation and 32% larger than ETo.

4.2.3 Model 3: Grass river banks

ET of grass was substantially limited by soil water availability and was thus 47% less than open water ET and 36% less than ETo. This water limitation was apparent between November and April when precipitation is insufficient to fulfil evaporative demand.

4.2.4 Model 4: Constructed wetlands with emergent vegetation (*Typha* sp.) connected to rivers

ET *for Typha* wetlands was estimated at 23% greater than ETo and 2% greater than open water, most likely due to the aerodynamic effect of the taller canopy.

4.2.5 Model 5: Water conservative, shallow-rooted native riparian plantings along waterways

As for grass, water availability limited ET of the simulated hypothetical water conservative, shallow-rooted riparian species. This result mirrors ET patterns for Matagouri (*Discaria toumatou*) in riparian zones in northern Canterbury (Dudley et al. 2018). Many woody species inhabiting riparian areas may rely on seasonally dry surface soils for water. As a result, despite a different canopy resistance and a higher threshold for soil water limitation, ET for this scenario was largely similar to that of grass. Annual ET was 45% lower than open water ET and 34% lower than ETo.

4.2.6 Model 6: Constructed wetlands without emergent vegetation connected to rivers

The original Penman equation for evaporation from an open water surface predicted an annual ET 17% greater on average than the equation for a well-watered reference crop (ET_o), likely due to the absence of any canopy (stomatal) resistance.

4.3 Key outcomes

ET in riparian areas will run the full spectrum of values from very high for willow and other wetland species with access to water throughout the year, to very low for seasonally dry grasslands and other water-conservative species which are limited by soil water balance. Our results suggest that this seasonal water deficit effect has the strongest influence on annual ET from riparian areas. Because the water deficit is highest during summer low-flow periods the greatest differences in ET between riparian vegetation with and without access to groundwater occurs during summer months (Figure 4-3).

At a regional scale, changes in the abundance of plant species that are not susceptible to soil water deficits – such as through introduction of invasive phreatophyte species or removal of large trees in place of shallow-rooted crops – may profoundly affect regional hydrology. Increased groundwater transpiration by deep-rooted plants (phreatophytes) may reduce base flow, as outlined earlier in this report.

A second dominant factor leading to differences in ET from riparian surfaces was canopy height. This was apparent in willow (at both 10 and 20 m canopy height) and *Typha* covers having ET greater than that of open water.

Finally, stomatal conductance (i.e., water ‘conservativeness’) accounted for differences in water use among species with similar access to water and a similar canopy height. In a comparison between riparian grass cover and a hypothetical water-conservative shrub species, water use over summer months was similar, despite the greater canopy height of the shrub cover. This suggests that it may be possible to reduce water loss by selecting water-conservative species at riparian boundaries, while still providing the benefits that taller riparian species provide to rivers (e.g., stream shading).

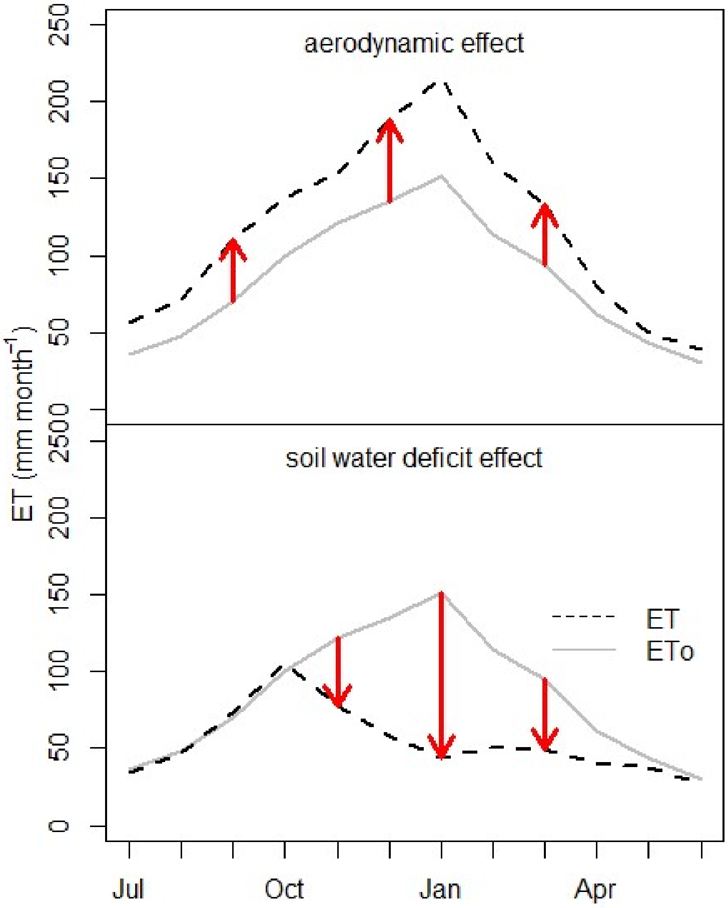

Figure 4-3: The difference between the grey and dashed lines in the upper plot is the 'aerodynamic effect. Comparison of aerodynamic effects and soil water deficit effects on ET. In both the upper and lower plots, the grey line shows ET from a well-watered reference grass surface (ETo), calculated according to Allen et al. (1998) using data from NIWA's climate station at Waipawa (39.9416°S; 176.5896°E) in the Hawke's Bay Region. The dashed line in the upper plot gives ET from tall canopy species with constant access to water and low stomatal conductance. The dashed line in the lower plot shows ET from riparian grasses where both transpiration and soil evaporation are constrained by the soil water balance. The difference between the grey and dashed lines in the lower plot is the 'soil water deficit effect'.

Overall, the six modelled riparian vegetation scenarios illustrate the three mechanisms by which riparian cover of willows may reduce river flows. Willows are typically situated either in river beds or on river banks where groundwater that feeds river flow is available to their shallow root systems. Therefore, they are unlikely to be water-limited even during summer months when shallow soils are dry. Secondly, willows have large, spreading canopies reaching heights of ca. 20 m; this leads to increased aerodynamic effects on canopy resistance (Figure 4-3). Finally, willows have high maximum stomatal conductance (i.e., not water-conservative). Furthermore, the seasonal progression of LAI at the Hawke's Bay study site dictates that the water use of willows is greatest during mid to late summer, when stream flows are likely to be lowest. Together, these factors explain the high water use and productivity of willows (and other species that share similar characteristics such as poplars), and the cause for concern regarding the influence of these species on river flows. The alternative riparian vegetation scenarios modelled offer some alternatives for reducing water use but, overall, more information is required regarding the extent to which these alternatives differ from willows in their water-use characteristics. This is discussed in Section 5.

5 Knowledge gaps

5.1 Riparian climate

The six riparian vegetation scenarios discussed in this report have been modelled using simplified, one-dimensional representations of vegetation water use. As such they are indicative of water use by a range of riparian options. However, riparian environments are complex both in respect to topography (which influences water availability) and vegetation distributions. Likewise, there are strong interactions between surface water, vegetation, and local climate. In this study we used climate data from an un-watered grass surface (i.e., pasture) to describe conditions of vapour pressure deficit (VPD) and temperature in a riparian area. VPD and temperature conditions may be considerably different in a riparian tree canopy and this would lead us to overestimate atmospheric sinks for water and thus aerodynamic water loss. This possibly resulted in an overestimate in the aerodynamic water loss of tall willow canopy. A more accurate estimate of willow ET could be attained by measurement of VPD and temperature within riparian areas of interest.

5.2 LAI

The LAI model coded for this report increases the accuracy with which we can represent the seasonal progression of LAI in willows (and other deciduous species). However, peak LAI in the model was held at 3, due to a lack of information on peak LAI for the Hawke’s Bay study site This is particularly important in the case of the 10 m trimmed willows treatment; the model as it stands only accounts for reduction in canopy height from trimming and assumes that leaf area remains identical to the 20 m scenario. A concerted investigation of LAI for a selected range of riparian species, and management options for willow, during a summer growing season could provide information that would improve the accuracy of model results, and the confidence with which we can make decisions.

5.3 Canopy resistance

In this report we used minimum canopy resistance values and responses to environmental drivers for crack willow (*Salix fragilis*) (Doody et al. 2006). Wide ranging values of minimum canopy resistance for willow species are reported in the literature review (Section 2), thus there is substantial uncertainty in our modelled estimates from the selection of these values. Stomatal conductance values, gathered for both willow and alternative riparian species, would greatly improve our ability to select riparian tree and shrub species with water-conservative traits.

5.4 Soil water holding capacity

Soil water holding capacity determines the seasonal progression of soil water deficit in soils. The modelling results presented in Section 4 demonstrate the importance of soil water deficit in controlling ET for grass, some shrubs and potentially many other species common to riparian areas. Site-specific understanding of soil water holding capacity is important to accurately develop estimates of ET for those riparian species that do not have root access to groundwater (or the capillary fringe) or stream water.

5.5 Feedbacks between stream flow and plant water use

Our one-dimensional simulations of water use can provide a relative water cost for different riparian vegetation scenarios. However, an assessment of the effect of these scenarios on catchment water yield requires at a least two-dimensional modelling approach (i.e., including the relative areal extent of riparian vegetation cover). An even better understanding could be gained by a three-dimensional approach that considers soil processes, including infiltration rates, depth to groundwater and soil moisture distributions.

5.6 Position of trees on bank and bank topography

In this project we compartmentalised the soil water balance for grass (i.e., stream water is not available to grass), while willows had permanent access to stream water all year round. In reality, the riparian environment probably represents a continuum from plants which are totally reliant on soil water to plants that have varying access to stream water. Key aspects that will determine the relative reliance of riparian plant species on soil water are the depth to groundwater (i.e., elevation relative to stream water and groundwater), and rooting depth. A potential method for assessing access to groundwater for specific riparian species over wide areas is to combine stable isotope and remote sensing data to generate maps of groundwater access. In this approach, stable isotope analysis of stem water, groundwater and soil water would provide the raw data with which to establish the proportion of transpired water derived from groundwater. These data could be regressed against parameters from remote sensing platforms that indicate water availability (e.g., tree height, elevation relative to the stream and leaf stress indices), and the regression relationships used to extrapolate relative access to groundwater over wide areas (Asner et al. 2016).

6 Summary and recommendations

The questions this study set out to address were:

1. Do willows used for river bank protection consume large amounts of water?
2. Do the evaporative basins of wetlands constructed to treat diffuse source pollution result in water loss from the system?
3. Should consideration be given to balancing increased water use by riparian trees against their ecological benefits, when deciding to plant native vegetation in riparian zones?

Lack of some plant eco-physiological data and site physical data reduced the surety with which we could quantify water use for the six modelled riparian vegetation cover scenarios. However, the results provide a good demonstration of the major factors controlling evaporative water loss from the study site that allow us to answer the questions above. These are:

- Climate – seasonal patterns in climate parameters, including radiation, vapour pressure deficit and water availability, exert tight controls over riparian evapotranspiration. Hence, the answers to the first two questions above are site-dependent. Water losses from tall riparian trees such as willow, and wetlands, are greatest in windy, hot, dry areas.
- The 'soil water deficit effect' – this was a key process influencing riparian evapotranspiration (ET), with the degree of influence dependent on the rooting depth for a given plant species, the depth to groundwater, and the soil water holding capacity at the site. Shallow rooting depths, greater depth to groundwater and reduced soil water holding capacity all reduce ET during summer months. Hence, water savings could be made by planting shallow-rooted species in riparian zones for which transpiration and growth are seasonally limited by water availability. With regard to question 3, above, the benefits of this approach are likely to be greatest in areas set back from water bodies where groundwater is shallow but tall, deep rooted vegetation does not provide ecological benefits important in riverside vegetation (e.g. shading and bank stability).
- Aerodynamic canopy effects – riparian vegetation with tall canopies resulted in greater evaporative water loss than those with short canopies. Hence, water savings could be made by planting shorter plant species in riparian zones. As above, this effort is likely to provide the greatest net ecological benefit in areas set back from water bodies where groundwater is still shallow.
- Stomatal conductance – this resulted in noticeable ET differences for riparian vegetation with similar access to water and canopy height. Selection of 'water conservative' riparian species would result in water savings.

Willows provide a good example of vegetation with high access to water, tall canopy and high stomatal conductance. The '20 m willow canopy' land cover had the highest ET of the six riparian cover scenarios modelled.

We identified knowledge gaps around site physical parameters and vegetation parameters that limit our ability to accurately estimate riparian ET. Aspects of site physical parameters where better knowledge is most needed to improve model confidence are:

- Site-specific estimates of catchment water yield – this requires at a least two-dimensional modelling approach (i.e., including relative areal extent of riparian vegetation covers). A better understanding could be gained by a three-dimensional approach that considers soil processes, including infiltration rates, depth to groundwater and soil moisture distributions
- Meteorological data from within the riparian area – the nearest meteorological station was located on unirrigated pasture that is unlikely to represent the meteorological conditions at the study site.

Aspects of vegetation ecophysiology most needed to improve model inputs, and hence model confidence, are:

- Maximum leaf area index (LAI) values for riparian plant species across New Zealand we used the method of Jolly et al. (2005) to calculate the seasonal progression of willow LAI from its seasonal maximum but seasonal maximum LAI values have not been adequately measured for either willow or other riparian species.
- Canopy resistance functions for riparian plant species –Penman-Monteith calculations are particularly sensitive to canopy resistance which is not well characterised for many New Zealand native species.

We see the collection of national datasets of the above two eco-physiological parameters as a useful further step towards the construction of a management tool to quantify water use for different riparian vegetation scenarios. However, we suggest that accurate, site-specific quantification of riparian evapotranspiration would still require considerable site investigation of the physical parameters mentioned above.

7 Glossary of abbreviations and terms

Aerodynamic resistance	The transfer of heat and water vapour from the evaporating surface into the air above the canopy, in terms of the Penman–Monteith model.
Canopy conductance/ resistance	Canopy conductance is a measurement that characterises radiation distribution in tree canopies. It is calculated as a ratio of daily water use to daily mean vapor pressure deficit (VPD). Stomatal conductance may be used as a reference value to validate data, by summing the total stomatal conductance of all leaf classes within the canopy. Canopy resistance is the inverse of canopy conductance.
Ecohydrological setting	Effects of hydrological processes on the distribution, structure, and function of an ecosystem, and with the effects of biotic processes on elements of the water cycle.
Ecophysiology	How the environment, both physical and biological, interacts with the physiology of an organism.
Evaporation	The transfer of water from liquid to vapour. Evaporation occurs from water bodies (e.g., lakes, rivers, ponds), from the ground surface, and from vegetation.
Evapotranspiration (ET)	Combination of evaporation from free water surfaces and transpiration of water from plant surfaces to the atmosphere.
Growing season index (GSI)	GSI models the effects of environmental constraints on canopy development and has proven to be useful as a prognostic model of Leaf Area Index (LAI).
HBRC	Hawke’s Bay Regional Council.
Hydraulic conductivity	A measure of the ease with which water flows through sediments, determining renewal rates of water, dissolved gases, and nutrients.
Hydrology	The occurrence, distribution, and circulation of water through the unending hydrologic cycle of: precipitation, consequent runoff, infiltration and storage, as well as evaporation.
Leaf Area Index (LAI)	An index used to characterise the amount of foliage in plant canopies, it is defined as: half the total leaf surface area per unit ground surface.
NIWA	National Institute of Water and Atmospheric Research.
Penman–Monteith model	An equation used to model evaporation from an open water surface from standard climatological records of sunshine, temperature, humidity and wind speed. This method has been further developed and extended to vegetated surfaces by introducing resistance factors, including aerodynamic resistance and surface resistance factors.
Photoperiod	Day length or the period of daily illumination received by an organism.
Photosynthesis	Process used by plants, algae and certain bacteria to harness energy from sunlight and turn it into chemical energy.

Plant phenology	Cyclic processes of vegetation, the timing of plant life-cycle events (e.g., seasonal patterns of leaf area and flowering).
Remote sensing	Process of detecting and monitoring the physical characteristics of an area by measuring its reflected and emitted radiation at a distance from the targeted area.
Riparian areas	Interface between terrestrial and aquatic ecosystems. The area of land that adjoins, regularly influences, or is influenced by, a waterbody.
Riparian vegetation	Composition of riparian plant communities. Increased soil moisture levels in riparian areas favour the development of particular species and plant communities, which may differ considerably in composition from those in adjacent upland areas. Riparian vegetation communities influence both the biological and physical components of the system.
Saturation deficit	Amount by which water vapor in the air must be increased to achieve saturation without changing the environmental temperature and pressure. The saturation deficit may be expressed in terms of a vapor pressure deficit (VPD), an absolute humidity deficit, or a relative humidity deficit.
Soil water deficit	The difference between the amount of water in the soil and the amount of water that the soil can hold.
Solar radiation	Radiant energy emitted by the sun, particularly electromagnetic energy.
Stomata	Small pores in a plant leaf, surrounded by guard cells that regulate opening and closure, that serve as the site for gas exchange.
Stomatal conductance/ resistance	Stomatal conductance is a measure of the degree of stomatal opening and can be used as an indicator of plant water status. It is the measure of the rate of passage of carbon dioxide (CO_2) entering, or water vapor exiting through the stomata of a leaf. Stomatal resistance is the inverse of stomatal conductance.
Transpiration	Vaporisation of liquid water contained in plant tissues and the vapour removal to the atmosphere.
Vapour pressure deficit (VPD)	VPD is defined as the deficit between the amount of moisture in the air and how much moisture the air can hold when it is saturated.
Water salvage	Defined as increased water availability for human or environmental beneficial use (both subsurface and surface waters), in the case of this report, as a consequence of vegetation and land cover change.

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