CHAPTER 1. EXECUTIVE SUMMARY

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1.1. Introduction

The movement of water through the whole continuum of the soil, vegetation, and atmosphere is an important process that we must learn to understand, and this process is central to the energy, carbon, and solute balances of the system. The total system is integrated and changes in one part of the system will affect the others. Therefore, it needs to be dealt with in an integrated way by considering the dynamic interactions and feedbacks between the processes.

Most of our current environmental problems arise from tampering with one or a few aspects of the system without any understanding of whole-system function. For example, in Australia much environmental degradation, including salinisation, is associated with changes in the near-surface water balance induced by massive clearing of native vegetation. These changes have led to significant increases in groundwater recharge, which in turn have led to rising watertables and salinisation. The temporal and spatial scales over which these changes evince themselves precludes field experimentation as a wholly sufficient or practical tool for identifying optimal or appropriate land use. The main emphasis of current salinity control strategies generally involves either improving the growth of existing annual crops and pastures or replacing these land systems with perennial vegetation. The idea here is to have larger leaf area and deeper roots so that plants can use the evapotranspirative capacity to remove more excess soil water and hence reduce recharge to groundwater. This is called biological drainage (Fig. 1.1) as opposed to engineering ones such as a ditch or well.

However, increased water use by plants could lead to larger upward flux of water and in the case of shallow saline groundwater tables this could cause salt to build up in the root zone. It is expected that the plant roots would die back and it would become more difficult for the plants to extract water. What would happen to the plants in the long run? Are these management options sustainable? The investment and uncertain ecohydrological returns demand a means to predict the expected effectiveness and sustainability of such schemes.

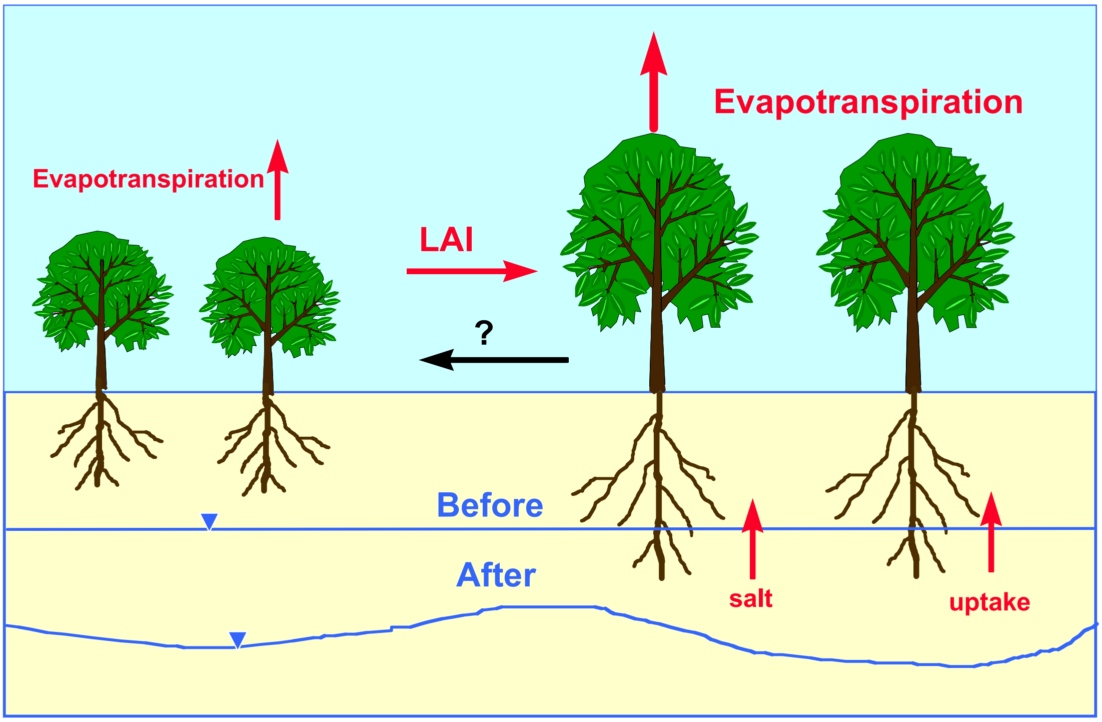

Fig. 1.1: Impact of salinity on plant growth and water use over shallow groundwater tables.

The hydrological cycle along with several other processes is influenced by vegetation through the exchange of energy, water, carbon and other substances. As a result, they are critical for many hydrological processes, in particular transpiration, infiltration, and runoff. The physiological response of vegetation when exposed to an increase in atmospheric carbon dioxide (CO_2) concentration could result in closure of stomata. Consequently, this could decrease evapotranspiration and affect surface water balance (See Fig. 1.2). The study of the biological controls of the hydrological cycle, and their ecological and environmental significance also requires an integrated approach that builds upon process understanding. This is essential for developing management strategies.

Models of the soil–vegetation–atmosphere system can be formulated at almost any level of complexity. All these models represent approximations of reality and include simplifications of the real process behaviour. Historically, process-based models have been developed to represent the system with increasing detail. When combined with appropriate data sources, such models have a great potential for exploring the interactions and feedbacks between processes and responses of the system under different management and/or climatic regimes.

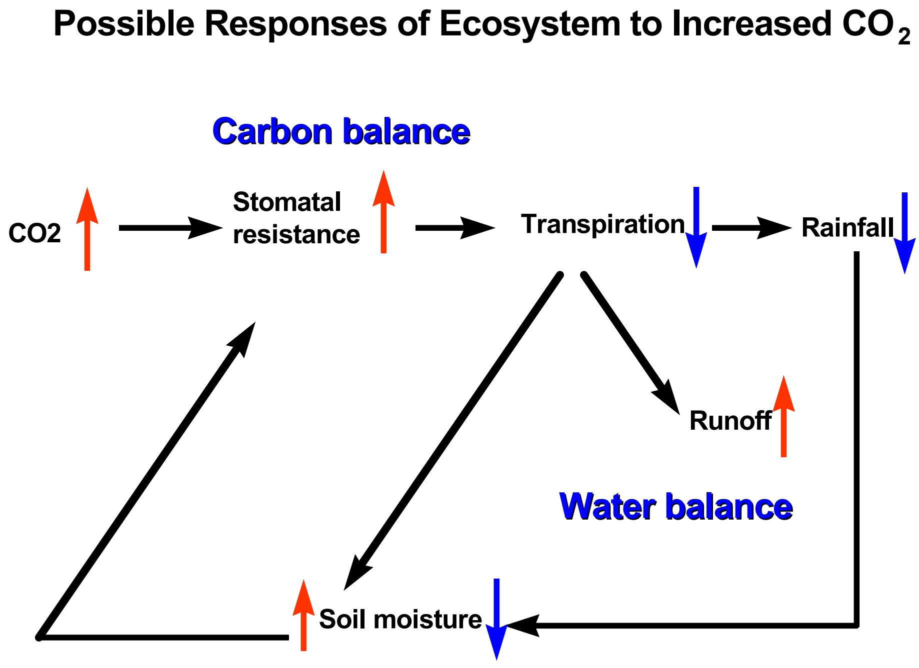

Fig. 1.2: Impact of climate change on the hydrological cycle and ecosystem.

1.2. Model Overview

WAVES is designed to simulate energy, water, carbon, and solute balances of a one-dimensional soil–canopy–atmosphere system (Dawes and Short, 1993, Zhang *et al.*, 1996). It is a process-based model and it integrates soil, canopy–atmosphere with a consistent level of process detail. WAVES predicts the dynamic interactions and feedbacks between the processes. Thus, the model is well-suited to investigations of hydrological and ecological responses to changes in land management and climatic variation, such as those discussed above.

WAVES models the following processes on a daily time-step:

- interception of rainfall and light by canopy
- surface energy balance
- carbon balance and plant growth
- soil evaporation and canopy evapotranspiration
- surface runoff and infiltration
- saturated/unsaturated soil moisture dynamics (soil water content with depth)
- drainage (recharge)
- solute transport of salt (NaCl)
- watertable interactions.

A diagram of the components of WAVES is shown in Fig. 1.3. The model is based on five balances:

- ***Energy Balance:*** partitions available energy into canopy and soil for plant growth and evapotranspiration (Beer's law);
- ***Water Balance:*** handles infiltration, runoff, evapotranspiration (Penman–Monteith equation), soil moisture redistribution (Richards equation), drainage, and water table interactions;
- ***Carbon Balance:*** calculates carbon assimilation using IRM and dynamically allocates carbon to leaves, stems, and roots, and to estimate canopy resistance for plant transpiration;
- ***Solute Balance***: estimates conservative solute transport within the soil column and the impact of salinity on plants (osmotic effect only);
- ***Balance*** of complexity, usefulness, and accuracy.

The energy balance module calculates net radiation from incoming solar radiation, air temperature, and humidity, then partitions it into canopy and soil available energy using Beer's law. Evapotranspiration is calculated using the Penman–Monteith equation (Monteith, 1981) with available energy, vapour pressure deficit, and air temperature as inputs. The Penman–Monteith equation is a 'big leaf' model based on the combination of energy balance and aerodynamic principles. It requires estimation of aerodynamic and canopy resistances. The aerodynamic resistance is estimated from wind speed and surface roughness, while canopy resistance is calculated as a function of net assimilation rate, vapour pressure deficit, and CO_2 concentration. WAVES couples canopy and atmosphere using the omega approach proposed by Jarvis and McNaughton (1986) and handles multi-layer canopy explicitly.

Water Vegetation Energy and Solute Modelling (WAVES)

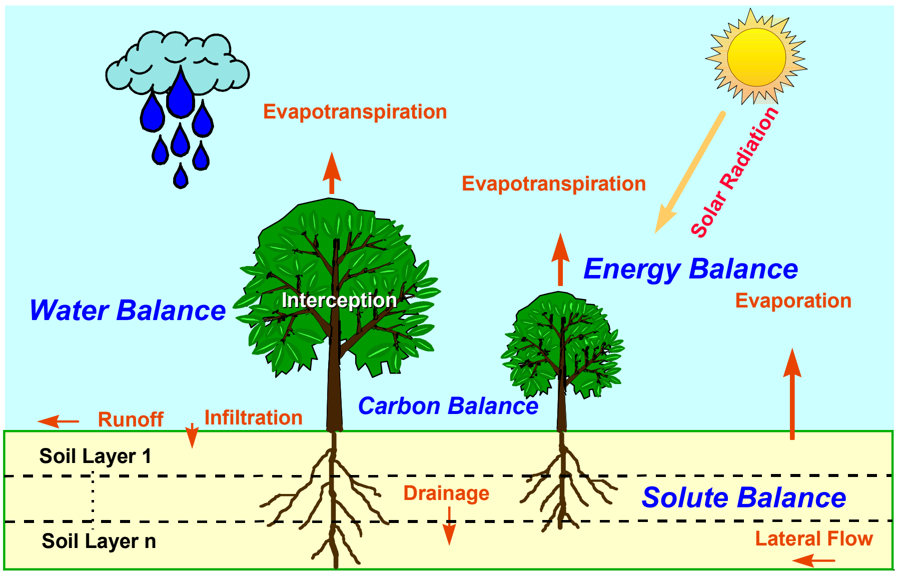

Fig. 1.3: Conceptual diagram showing the major processes modelled by WAVES.

WAVES is a daily time-step model, and it is assumed that the canopy and ground surface temperatures are equal to the average daily air temperature. This assumption does not introduce much error in the energy balance for relatively dense plant stands with non-limiting water supply (Zhang *et al.*, 1996). The ground heat flux is neglected in the energy balance equation because over land surfaces the daily mean value of the ground heat flux is one or more orders of magnitude smaller than the net radiation.

The carbon balance and plant growth module is based primarily on calculating actual daily carbon assimilation from a maximum value, and the relative availability of light, water, and nutrients; the limiting effects of temperature and salt in the soil water on assimilation are modelled explicitly. It is assumed that the actual growth rate is dependent on the potential growth rate and the level of the available resources. To combine the three limiting factors on plant growth into a single scalar we use the integrated rate methodology (IRM) of Wu *et al*. (1994), which allows other limiting factors, such as atmospheric CO_2 concentration, to be easily included. Once actual carbon assimilation is calculated, it is used as input to dynamic allocation of carbon to leaves, stems, and roots, and into the calculation of canopy resistance for transpiration (Slavich *et al.*, 1998).

The soil water balance module handles rainfall infiltration, overland flow, soil and plant water extraction, moisture redistribution, drainage (recharge), and water table interactions. Soil water movement in both the unsaturated and saturated zones is simulated using a fully implicit finite-difference numerical solution of a mixed form of the Richards' equation (Richards 1931, Dawes and Short 1993, Short *et al*. 1995). A full description of Richards' equation solution can be found in Dawes and Short (1993). Overland flow can be generated when the rainfall rate exceeds the infiltration rate of the soil, and when rain falls on a saturated surface. Both of the mechanisms are considered explicitly in WAVES. A watertable may develop anywhere within the soil profile. If non-zero slope is specified as input, then lateral subsurface flow occurs via any saturated water table at a soil layer boundary, and is described by Darcy's law. A regional groundwater depth may be specified, and changed on a daily basis with weather, and interacts with the WAVES soil column. Evaporation and transpiration draw water out of the soil, and when the internal saturated water level is below the regional watertable, leakage into the column occurs and may bring salt with it. Conversely, when the internal water level is above the regional watertable, due to plant inactivity or large amounts of infiltration, water may leak out of the column and leach salts.

To solve Richards' equation, the analytical soil model of Broadbridge and White (1988) is used to describe the relationships among water potential, volumetric water content and hydraulic conductivity. This soil model has five parameters: saturated hydraulic conductivity, volumetric soil moisture content at saturation, air-dry volumetric water content, the soil capillary length scale, and a soil structure parameter. The Broadbridge and White (1988) soil model can realistically represent a comprehensive range of soil moisture characteristics, from highly nonlinear associated with a well-developed capillary fringe, to weakly nonlinear associated with highly structured soil and macropores.

The assumptions of the Richards equation is that the soil is incompressible, non-hysteretic and isothermal, and that moisture moves in a single phase only. It also assumes that flow is via the soil matrix only, and not via macropores and larger preferred pathways. The soil is assumed to isotropic for the formulation of Darcy's equation for lateral movement. Any water ponded on the surface can either be left to pond, or appear as runoff within the time-step. Soil air flow is ignored.

Solute transport within the soil column is solved with a convection-dispersion equation, in the same way as soil moisture dynamics (Dawes and Short, 1993). It is assumed that the solute concentration does not interact with soil hydraulic properties, so water fluxes and contents are constants with respect to the solutes, and that salt never crystallises out of solution. This makes the solution of solute dynamics an explicit solution. The feedback to plants of salinity is through the reduction in apparent available water due to the osmotic potential induced by dissolved salt (sodium chloride) alone.

WAVES emphasises the physical aspects of soil water fluxes and the physiological control of water loss through transpiration. It can be used to simulate the hydrological and ecological effects of scenario management options (e.g. for recharge control). The model strikes a good balance between generality, realism and accuracy, and provides a powerful tool for recharge study.

1.3. Strengths and Weaknesses

The strengths of WAVES are:

- WAVES is a generic model not specifically designed for any particular climatic region, soil types, or vegetation systems. WAVES represents a wide range of dynamic processes, with appropriate feedbacks, at a consistent level of complexity. It strikes a good balance between complexity, usefulness, and accuracy.
- Weather data requirements are readily available. The minimum dataset comprises daily maximum and minimum air temperatures, and daily rainfall.
- The soil parameters used in WAVES are physical quantities that can be readily measured or estimated.
- WAVES can perform long-term simulations for as much weather data as is available or can be generated.

- WAVES is a DOS-based program not requiring Windows, and all output is in standard ASCII files that can be read into any commercial graphing software. It is quick to run, requiring about 2–3 seconds per year of simulation on a Pentium, regardless of which combination of processes is being simulated.
- WAVES has been extensively tested and the results have been published in international journals. Test sites include HAPEX-MOBILHY in France and FIFE in USA (Zhang *et al.*, 1996), Hillston in New South Wales and Walpeup in Victoria (Zhang *et al.*, 1999*a*), Loddon–Campaspe catchments in Victoria (Salama *et al.*, 1999), Griffith in New South Wales (Zhang *et al.*, 1999*b*), the North China Plain in China (Wang *et al.*, 1997), Chowilla in South Australia (Slavich *et al.*, 1998), North Stradbroke Island in Queensland (Green *et al.*, 1997*a*), and the Swan Coastal Plain in Western Australia (Green *et al.*, 1997*b*).

The weaknesses are:

- WAVES is a one-dimensional model, although the effects of slope and aspect on intercepted radiation and local lateral movement in water tables are incorporated.
- The form of Richards' equation used in WAVES assumes that there are no thermal effects on water flow, that the soil does not shrink or swell, and that the soil is non-hysteretic. Macropores, preferred pathways, and cracking soils cannot be modelled explicitly with WAVES, unless these effects can be represented within the soil hydraulic model.
- WAVES is a daily time-step model, and process representations are simplified to match this, and smaller time scale phenomena are not modelled.
- The generic plant growth model in WAVES is designed for looking at the hydrological impact of plants and does not model plant phenology, or dynamically fill grain. Estimation of grain yield from crops is through use of two forms of the Harvest Index. WAVES does not allow dynamic selection of vegetation type.
- WAVES uses an abstraction of relative nutrition, and does not perform nutrient cycling and leaching.

1.4. Data Requirements

WAVES requires three types of data: (i) meteorological data; (ii) soil parameters; and (iii) vegetation parameters. The meteorological data required are maximum and minimum daily air temperature, daily average vapour pressure deficit, rainfall, rainfall duration, daily solar radiation. Some or all of these data are available from weather stations, and with only the temperatures and rainfall, realistic estimates of the other data can be made. The soil data required is knowledge of the soil layering, and the parameters that describe the relationships between ψ (soil water potential), θ (volumetric water content), and K (hydraulic conductivity). Use of the Broadbridge–White soil model allows WAVES to guarantee accuracy and convergence of the water dynamics. For plant growth and the calculation of the energy balance, WAVES requires 22 vegetation parameters. Most of these can be measured directly or taken from plant physiological literature, with only a few remaining for fitting, or adapting to local conditions. Hodges (1992), Vertessy *et al.* (1996), Hatton *et al*. (1995), Salama *et al*. (1999), and Zhang *et al*. (1999*a,b*) have published the sources and values of the parameters used in the WAVES vegetation growth module.

1.5. Model Availability

The WAVES model software (including source code) plus documentation is supplied free of charge through collaboration or direct application to CSIRO Land and Water. The documentation and executables (Version 3.5) will be available on the WWW in 2000.