CSIRO

Land Use and Catchment Water Balance

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CSIRO Land and Water

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CSIRO LAND and WATER

PREFACE

The study of catchments has been part of the core business of CSIRO for many years. In no small part due to this research, Australia is more aware of our natural legacy, the importance of our catchments to our well being, the profound changes in catchment function and health we have brought about, and the opportunities and challenges ahead.

Catchment science embodies diverse fields of research, from detailed physics and chemistry, to biology and ecology, to mathematics and statistics, to sociology and economics. The integration of this knowledge is itself a science. The provision of sound technical underpinning to catchment management is a continuing and rewarding scientific challenge.

CSIRO Land and Water maintains a strong commitment to catchment science in aid of improving the lives of Australians and their environment. Part of that commitment involves reviewing our recent scientific accomplishments, our current research portfolio, and the direction our research needs to take into the future.

This series of reports captures CSIRO Land and Water research in catchment science since 1993, some of the current directions, and where our research should take us. We hope that this serves as basis for continual discussion and active debate on the nature and value of science to issues of high national importance like the health of our catchments.

Technical Reports in this series are:

No: 18: Land Use and Catchment Water Balance: Tom Hatton

No. 19: Catchment solute Balance: Glen Walker

No. 20: Sediment Nutrient Transport and Budgetting: Chris Moran (and contributors)

No. 21: Integrated Catchment Science: Rob Vertessy

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BACKGROUND TO THIS PAPER

On 4 July 2000, CSIRO Land and Water undertook a catchment review to ensure the quality and direction of the catchment science. Results will impact on our strategic direction and resourcing.

The approach used to review catchment science involved first a set of papers that capture the scientific outputs and future directions in each of four areas:

1. Land Use, Climate and the Catchment Water Balance
2. Catchment Solute Balance
3. Catchment Sediment and Nutrient Balance
4. Integrated Catchment Science

Each review paper is to:

(a) capture the whole peer-reviewed literature generated by CLW since 1993;

(b) describe the original questions and issues driving the research;

(c) describe how this research sits with respect to the international literature;

(d) describe how the issues and questions have changed;

(e) speculate on future directions.

The key issue for this review is the change in catchment water balance as a function of land use and climate. This is also a key issue for the topic 'Catchment Solute Balance', being led by Glen Walker. It is inevitable that there will be some overlap between these topics. For the sake of drawing boundaries, it will be assumed that this review will deal with recharge, groundwater response and risk of land salinisation. Glen's review will use the framework of the solute balance of a catchment to deal with management of saline land, stream salinisation and groundwater salinisation. These two reviews relate directly to projects 4 (title 1) and 5 (title2) of the Dryland Farming and Catchment Care Multi-Divisional Program, which ran from 7/95-7/00. These topics are also central to Component 6 (Landscape Remediation) and Component 8 (Sustaining Regional Development and Renewal) of the CSIRO Land and Water Sector Plan for 2000-2003.

THE SIGNIFICANCE OF LAND USE CHANGE ON HYDROLOGY IN AUSTRALIA

Where (and probably *wherever*) native (especially woody) vegetation has been perturbed or cleared in pursuit of economic development, the resulting (often subtle) changes in the surface and groundwater balance and flow lead ultimately to profound changes in catchment and ecosystem health. These water balance responses following land use change result in land and river salinisation, changed flood frequency and flow regime, and increased surface waterlogging, with all the associated ecological and economic impacts.

For instance, at present 2.1 M hectares of land is affected by human induced dryland salinity; most of the streams and rivers of southern Australia have salinised or continue to salinise. As much as 10-15 Mha are at risk to salinisation in the future (an area equivalent to that currently farmed in Victoria). Waterlogging affects crop and pasture productivity across millions hectares of land.

Changes in river salinity are compounded by changes in flow regimes and water yield associated with land use, climate variation, climate change and water allocation. Water resource policy reform is forcing a number of issues in catchment management including local governance, market-based allocation, allocation to the environment, and the development of credit or levy-based means of balancing private and public good issues. All of this must be viewed against a background of surface and groundwater resources that are already largely developed across southern Australia and in many cases over-allocated. While this is less true in northern Australia, in some areas groundwater extraction in this less-developed region has led to significant reductions in baseflow during the dry season. Because of the prolonged dry season in tropical Australia, rivers rely entirely on groundwater for flows at this time, and so river flows are extremely susceptible to groundwater withdrawals.

THE SCOPE OF THIS REVIEW

The scope of this review is restricted to the following areas in catchment science:

- The relationships among climate, land use and catchment hydrology.
- The pathways water takes through catchments.
- The interaction between catchment water balance and land and river salinisation.
- Monitoring the trend and condition of catchments.

The following related areas are considered outside of the scope of this review:

- Socio-economic aspects of land use and catchment hydrology.
- Land use and soil acidification.
- The special case of acid sulfate soils and their interaction with groundwater levels.
- Issues related to sediment and nutrient flow.
- The management of salinised resources.

CATCHMENT MANAGEMENT ISSUES AND SCIENTIFIC PERSPECTIVES IN 1992

In the early 1990's, Australia experienced a growing awareness of environmental issues, many associated with hydrological phenomena. Dryland and river salinisation, inland water eutrophication, and soil acidification became of growing concern, adding to longer-standing worries about soil erosion and habitat loss. In response to this growing awareness, the Billion Trees Program (1988) was launched, followed by a national Decade of Landcare (1989-1999). In the mid-1990's, a portion of the sale of the national telecommunications carrier was used to establish the Natural Heritage Trust, a fund for land and water care activities particularly at the local community level. All of these programs raised public expectations for action and results.

Looking back on the paradigms of the day, we note the following widely held beliefs of that time related to catchment management:

- Non-commercial, small-scale plantings of trees on farms would be an effective control on the spread or even reversal of dryland salinity.
- Trees act as “pumps” and were attributed enormous capacities to use water, could enhance groundwater discharge and thus were planted in saline discharge areas.
- Some species of trees used more water than others under the same conditions.
- Water use of traditional annual crops and pastures could be manipulated to effectively control salinity and perhaps acidification.
- Biodiversity could be maintained through the protection of remnant vegetation from clearing and perhaps grazing.
- Whole catchments must be managed to achieve downstream benefits.
- River salinity in the Murray-Darling Basin mostly resulted from irrigation developments.
- Concerns over environmental flows focussed on surface water.
- All catchments could be divided into recharge and discharge areas, with preferred recharge areas a target for remediation.

At that time, catchment science in the divisions that later became CSIRO Land and Water, began research that asked the following questions aimed at underpinning Australia’s response to land and water degradation. Much of this research was targeted at how land (and water) use affected catchment hydrology, ecosystems and industry. Specific questions addressed included:

- How can we better measure the actual fluxes of water through all its diverse pathways through catchments, and at the appropriate spatial and temporal scale?

- Can we build models of catchment behaviour from the bottom-up, able to forecast the likely outcomes from a variety of land use options against the background of climate variability?
- Can we make generalities between vegetation cover, climate and hydrology? Can we translate these generalities into useful, empirical, quantitative design guidelines for land use?
- Can we better characterise the interactions between trees and catchments? Does species matter, and when? How much transpiration is derived from soil water, and what potential do trees have to take groundwater? How sustainable and effective are tree plantings in the presence of saline watertables, and what makes natural forests sustainable in such situations?
- What is the sustainable yield of ground and surface water resources? What are the environmental flow requirements associated with these resources?
- What is the scale of revegetation required to control or reverse dryland salinity? Where is it possible?
- What is the coupling between the land surface and the atmosphere?
- How do regional projections for climate change translate to local changes in precipitation and runoff?
- How does water actually move through catchments? How coupled are surface waters and groundwaters?
- What different types of catchment exist with respect to salinity risk?

It is important to note the following as background to the challenges implicit in the above research objectives:

- Australia is a very large nation, with a small, mostly urban population. Most of the nation is remote, and there are limited resources for investigations and monitoring. *Catchment data is sparse and often of only short duration*. *Basic knowledge regarding catchment function is limited.*

- *Most people live in the southern half of the continent*, and this is where the major impacts of land use are focussed.

- It is a continent of generally *low relief* (mean elevation 200m), very *weathered regolith* on very *old geology*.

- It is the driest inhabited continent, *with annual variability in rainfall generally greater than seasonal variability*; only southern Africa has similar variability in annual rainfall and streamflow.

HOW TO INTERPRET THE INCLUSION OF REFERENCES IN THIS DOCUMENT

The purpose of this review is to establish the scientific progress and future direction of catchment science in CSIRO land and Water. As such, the references included in this document must reflect not only our *productivity* but also our *capacity*. Thus we include references from CSIRO staff since 1993, including some literature that staff may have generated before they joined CSIRO. This is justified in that we are trying to capture the capacity, direction, philosophy and continuity of the science and the scientists currently in CLW.

We have also limited the content of this review to peer-reviewed journal papers or book chapters, but have included papers submitted to those outlets that have gone through internal peer review (these are identified as published in 2000 in the body of text but clearly identified as "submitted" in the reference lists). We have also included articles that review our work.

The following notation is used in the references to make these features clear:

- ✓ Authors working for CSIRO Land and Water are identified in bold.
- ✓ A leading asterisk identifies non-peer reviewed material papers.
- ✓ Papers generated prior to staff joining CSIRO are in Italics.
- ✓ For selected papers, number emboldened in parentheses indicates the number of citations as of September 2000 in Scientific Citation Index. Please note that only a selection of papers, mostly published before 1998, was selected for assessment by this means.

UNDERSTANDING CATCHMENT FUNCTION

Since 1993, CLW has made significant advances in methods and advancement of knowledge about Australian hydrological processes. This work is crucial for underpinning prediction and management of our catchments.

CLIMATE, ATMOSPHERE AND THE LAND SURFACE

Two key areas of atmospheric research in CLW bear directly on catchment water balance.

(a) Transfer of water vapour between the ground and leaf surfaces through to the atmospheric boundary layer

Most land use change impacts result from changes in the surface energy balance and return of water to the atmosphere. Significant scientific challenges remain in understanding the behaviour of land surface – atmosphere interactions. These include the development of theory to scale and regionalise fluxes of water vapour and energy in heterogenous landscape and complex terrain, understanding the degree and nature of physiological controls on transpiration, and characterising the sources and sinks for energy, trace gases and water vapour.

Advances since 1993 include:

- Regionalisation of atmospheric fluxes in heterogeneous or complex terrain (Denmead *et al.* 1996; McNaughton and Raupach 1996; Raupach and Finnigan 1995).
- Identification of emergent properties of land surface – atmosphere interactions, such as the negative feedbacks which control regional-scale evaporation, surface energy balance and atmospheric boundary layer development (Pielke *et al.* 1998; Raupach 1998; Raupach 2000a,b).
- Scaling of fluxes and conductances from leaf to atmosphere (Raupach 1995; Raupach and Finnigan 1995; Raupach *et al.* 2000).
- Identifying and quantifying sources and sinks in land surface-atmosphere interactions (Raupach *et al.* 1997; Raupach 2000c).
- Recognition and modelling of the coupling between water, energy and CO2 fluxes between land and air (e.g. Leuning 1995; Raupach *et al.* 1997, Raupach 1998, Leuning *et al.* 1998; Wang and Leuning 1998)

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(b) Spatial and temporal interpolation of surface temperatures, rainfall and soil moisture at regional scales

Sparse data and short term monitoring are characteristic of Australian hydrological and meteorological data. The need to extend and interpolate such data is critical to catchment understanding prediction.

A major concern on the future of Australian catchments, the water they supply and their overall health regards forecasts of global climate change. However, translation of forecasts at that scale to changes in the hydrological behaviour of local catchments is a significant scientific challenge.

Since 1993, CLW has made the following advances in this area:

- Development of techniques to extrapolate rainfall and other meteorological data in space and time (McVicar and Jupp 1999; Hughes *et al.* 1999; Jothityangkoon *et al.* 2000; Zoppou *et al.* 2000).

- The means to spatially interpolate soil moisture across large regions on a daily basis (McVicar and Jupp 2000).

- A technique to infer daily evaporation from instantaneous measurements, allowing the potential to ultimately infer this quantity from remotely sensed satellite data (Zhang and Lemeur 1995; Zhang *et al.* 1995).

- The development of techniques for downscaling GCM predictions to their impacts on local rainfall and catchment response (Bates *et al.* 1998; Charles *et al.* 1999a,b; Bates *et al.* 2000).

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Current Research in Climate, Atmosphere and the Land Surface *Related to Catchment Science*

- Development of a state-of-the-art model for exchanges of energy, mass, and momentum between land surfaces and the atmosphere, and to adapt it to serve both the climate and agricultural systems modelling communities.

- Development of techniques applicable at several scales for verifying the predictions models of land-atmosphere fluxes of energy, water, and CO2, including the development of remote flux-measurement capabilities.

- Obtain new knowledge about, and develop predictive models for, the transfer of hydroclimatic information across space and/or time scales that include variability and uncertainty.

- Develop and test improved statistical-dynamical tools for the analysis of atmospheric and hydrologic processes, climate variability, possible climate change, and their impacts on hydrologic systems and aquatic ecosystems.

LANDSCAPE HYDROLOGY – DESCRIPTION

The characterisation of the structure and hydrological function of the regolith is fundamental to understanding the impacts of land use on catchments. Research undertaken in CLW since 1993 has developed new ways to measure or infer catchment structure and function, and has applied these methods to a number of Australian key surface and groundwater systems.

New Investigative Methods for Landscape Hydrology

The capacity to describe Australian hydrological systems by traditional means is limited. Experimental approaches involving perturbation of the system generally take too long to yield results that can be measured. CLW has been active in developing techniques for indirectly inferring hydrological processes that integrate over long time and spatial scales.

Advances since 1993 include:

- Better understanding of isotopic fractionation of water in the environment and the interpretation of soil isotopic information (Tyler and Walker 1998; Barnes and Turner 1997).

- Improvements in the application of electromagnetic induction techniques, remote sensing and spatial analysis for the identification of groundwater recharge and discharge areas, and the salt content of the regolith (Salama *et al.* 1994; Bui *et al.* 1996; Cook and Williams 1998).

- Application of environmental tracers to determine residence times of groundwater and solutes, and the pathways they take through hydrological systems (Cook and Solomon 1997; Cook and Bohlke 1999; Cook and Dighton 1999; Coplen *et al.* 1999; Herczeg and Edmonds 1999; Salama 1996; Turner and Barnes 1998; Solomon and Cook 1999; Cook and Simmons 2000).

- Applied research dealing with the accuracy of spatial data and the influences of spatial error on agricultural management. A generic tool was developed and is available from the WWW to quantify positional accuracy for digital geospatial data (Van Neil and McVicar 2000).

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Characterisation of surface and near-surface hydrological processes

It is becoming increasingly apparent that our understanding of local-scale hillslope processes is more limited than perhaps previously believed. There is a growing appreciation that heterogeneity at the local scale is not only high, but also functionally quite important. The general failure of simplistic hillslope models based on soil physics and equally simplistic conceptual models of the regolith to adequately describe flow greatly compromises our ability to project the likely impacts of land use change on our catchments.

Since 1993, CLW has made limited advances in this area:

- The application of functional pedology as an aid in interpreting soil hydrological processes (Cox *et al.* 1996).
- Better understanding of local-scale variation in runoff generation in upland forests (Croke *et al.* 1999).

Application of tracer techniques to partition surface runoff, preferential throughflow and deep drainage (Leaney *et al.* 1993).

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Characterisation of Groundwater Systems

Issues related to groundwater allocation, and the management of recharge and discharge, depend crucially on the characterisation of aquifer properties and fluxes. Part of the work in CLW over the past decade has involved regional scale studies of sedimentary groundwater systems with an emphasis on long-term gross estimates of water fluxes (recharge and discharge). The work has involved both conventional (hydraulics) and the use of a range of environmental isotopes that integrate over the time scales commensurate with water residence time of groundwater within large aquifers. Due to very large head variations in groundwater imposed by global climatic changes on the order of 10^3-10^5 years, estimates of groundwater discharge based on present day hydraulic heads in large regional systems are effectively transient. Our research has indicated almost universal hydrologic disequilibrium in aquifer systems in semi-arid Australia – that is, they are in a state of net discharge. Management of these resources that purport to maintain systems in a state of "sustainable development" based on a premise: allocation = recharge = allocatable resource, are clearly inappropriate.

Significant achievements since 1993 include:

- A comprehensive review of techniques to estimate and model groundwater flow processes (Armstrong and Narayan 1998).
- Application of tracers and groundwater modelling to identify and quantify flow processes in large, regional aquifers (Love *et al.* 1993, 1994; Dogramaci *et al.* 2000).

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Current Research in Landscape Hydrology - Description *Related to Catchment Science*

- The use and analysis of hyperspectral remotely sensed data, specifically in the area of vegetation mapping, and coastal and inland optical water quality measurement.
- The development of new applications to remotely sensed data through strong emphasis on ground-based measurement/validation and radiative-transfer modelling.
- Develop expertise in the analysis and use of new key technologies such as polarimetric radar and profiling laser for assessment of land-cover structure and topography.
- Research on the use of remotely sensed data to measure land-cover function directly or via soil-plant-atmosphere models.
- Further development of the field of regional integration and analysis of time-series of remotely sensed data to provide predictive tools assessment and forecasting of landscape degradation. These tools will provide an ability to monitor changes in state, characterise driving variables, and predict system response.
- Develop generic methods for the spatial prediction of soil and land properties with particular emphasis on those controlling the soil-water balance.

- Develop new methods for characterising groundwater flow and solute transport in fractured rock aquifers. Such aquifers are currently very poorly understood. Catchments include Clare Valley (SA), Atherton (Qld), and Darwin (NT).

- Quantify groundwater recharge to regional groundwater systems using a range of techniques, especially groundwater tracer methods.

- On the basis of theoretical recharge-discharge relationships and landscape evolution, develop methods to infer aquifer characteristics in an extensive way. Relate this understanding to a classification of Australian catchments that distinguishes their responses to land use change.

ESTIMATING AND SOURCING TRANSPIRATION

Because land use change normally involves changing the type, structure or density of vegetation, understanding how the transpiration term of the water balance varies with these changes is central to predicting catchment response. Additionally, knowing the degree to which vegetation may be dependent on groundwater is vital in identifying both the effectiveness of revegetation schemes on controlling phenomena like salinisation as well as for ensuring the environmental allocation of groundwater resources to dependent ecosystems.

Estimating the Volumes of Transpired Water

CLW has developed a national and international reputation in the measurement of transpiration. This includes the development, improvement and commercialisation of measurement techniques, and their application is a wide variety of environments.

Significant scientific accomplishments since 1993 include:

- The widespread and robust estimation of tree transpiration under a variety of conditions and species (Farrington *et al.* 1994, 1996;Barrett *et al.* 1995, 1996; Vertessy *et al.* 1997). This work included the commercialisation of sapflow technology now widely adopted in Australia and overseas; application of such technology has made transpiration measurements in woody plants a routine and common component in catchment investigations. This work has resulted in more realistic estimates of transpiration (up to perhaps 1200 mm per year at sites with unlimited water, as opposed to previous estimates reported as high as 4500 mm per year). It has also helped us understand the ecophysiological basis for ecotones between forest types along topographic gradients in catchments (Barrett *et al.* 1996), and the interaction between flooding and tree water use (Jolly and Walker 1996).

- Methods to scale tree estimates to whole stands were developed and again are widely adopted outside of CLW (Hatton and Wu 1995; Hatton *et al.* 1995; Taylor *et al.* (a), submitted).

- The reasonably robust hypothesis that seasonal transpiration per unit leaf area does not significantly vary among species of eucalypt and perhaps among other genera (Hatton *et al.* 1998). This greatly simplifies revegetation design guidelines for hydrological control.

- Complementing sapflow measurements with micrometeorological measurements has helped to understand the partitioning of overstory transpiration from understory transpiration and soil evaporation (Cook *et al.* 1998; Silberstein *et al.*, submitted), as well as edge effects on plantation water use (Taylor *et al.* (b), submitted).

- Transpiration studies in the presence of high saline watertables has been crucial in assessing the potential growth, survival and site impacts of revegetation or natural vegetation (Bleby *et al.* 1997; Hatton *et al.* 1998; Slavich *et al.* 1999).

- Humphreys *et al.* (1994) developed a robust picture of evapotranspiration from irrigated rice through an extensive review of previous work. The water balance of irrigation areas along inland river systems is an important feature of river salinisation and allocation.

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Determining the Origin of Transpired Water

Because groundwater and its management is such an important feature of catchment management, knowing the degree to which vegetation is reliant upon and exploits groundwater, and under what conditions, is an important feature of Australian catchment science. CLW has a long history of the application of environmental isotope chemistry to research questions such as these.

Significant achievements since 1993 include:

- Significant improvements have been made in techniques for applying naturally occurring stable isotope analyses to assess sources of plant water (Brunel *et al.* 1995, 1997; Walker *et al.* 1994, 2000).

These methods have been applied to a number of systems including riparian forests (Thorburn *et al.* 1993; Mensforth *et al.* 1994; Thorburn and Walker 1994; Thorburn *et al.* 1994), tree plantations (Salama *et al.* 1994), and irrigated lucerne in the presence of a saline watertable (Zhang *et al.* 1999).

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From the above studies, the following generalisations have emerged:

- A number of Australian plant communities have a degree of dependency on groundwater through the dry season. This knowledge has important implications to allocating groundwater resources to the environment, not previously appreciated.
- Groundwater use typically depends on demand, surface soil moisture status, groundwater depth and quality. Local models of this response surface can help establish the constraints to groundwater development.
- There are definite and serious constraints on the long-term survival of trees planted in net groundwater discharge areas where saline, in the absence of effective leaching phenomena. The implications of this knowledge are both serious and immediate, for a major thrust of Landcare plantings of trees has focussed on such sites.

Current Research in Estimating and Sourcing Transpiration *Related to Catchment Science*

- Estimating the edge effect of local groundwater system on a *Banksia* woodland in WA.
- Groundwater and water quality dependency of *Banksia, Casuarina* and *Melaleuca* species in an estuarine ecosystem subject to flooding.

PREDICTING CATCHMENT RESPONSE

Empirical Understanding and Modelling of Rainfall-Runoff Relationships

Given sparse data on soil and regolith properties in the presence of remarkably complex surface hydrology and hydrogeology, as well as the complications leading from other parts of the catchment water balance, a large effort has gone into the development and interpretation of empirical relationships between rainfall and runoff.

The chief accomplishments since 1993 are:

- Improved methods for estimating and optimising model parameters and model sensitivity (Salama *et al.* 1996; Sivapalan *et al.* 1997; Campbell *et al.* 1999; Thyer *et al.* 1999; Bates and Campbell 2000).

- Application of empirical models to the hydrological impacts of climate change (Bates *et al.* 1994; Chiew *et al.* 1996; Simpson *et al.* 1993a,b; Thomas and Bates 2000).

- Regionalisation of rainfall-runoff and flooding characteristics from gauged to ungauged systems (Post and Jakeman 1996, 1999; Bates *et al.* 1998; Post *et al.* 1998; Rahman *et al.* 1999; Campbell and Bates 2000).

- Calibration of rainfall-runoff models for forecasting and understanding process in catchments (Bates *et al.* 1993; Sumner *et al.* 1997; Post and Jones 2000).

- Advances on the long-standing problem of introducing land use change into empirical hydrological models (Post *et al.* 1996; McVicar *et al.* 2000).

- The development and robust testing of simple empirical relationships between annual rainfall and runoff for forested and nonforested catchments, which appears to hold worldwide (Zhang *et al.* 2000). The application of these relationships to Australian catchments has highlighted profound and unexpected impacts on river salinity and water supply under plans for large-scale commercial afforestation of the highlands of Victoria and New South Wales.

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Catchment Prediction – Process-based

The advent of fast computers, the availability of remotely sensed data and efficient numerical methods gave rise to a number of efforts to construct plot and catchment scale water balance models based on “bottom-up” logic. The attraction of these models was the belief that they could be used to test hypotheses related to land use change as an alternative to field experimentation at scale and over necessarily long time frames. These models (and others) are reviewed in Hatton *et al.* (1998). Since 1993, the following advances were made in this area:

- The development of regional scale, distributed parameter, grid-based applications of point water balance modelling driven by changes in vegetation cover as sensed by satellites (Hatton *et al.* 1993, Pierce *et al.* 1993)

- The development of topographically-driven, physically-based, distributed parameters catchment models such as TOPOG (Dawes and Short 1995; Short *et al.* 1995; Vertessy *et al.* 1993).

- The development of basin scale models of river flow and salt loads based on remotely sensed vegetation cover and limited parameter optimisation (Sivapalan and Viney 1994; Sivapalan *et al.* 1996c; Viney and Sivapalan 2000).

- Analytical techniques developed and applied to evaluating model sensitivity to parameter estimation (Ye *et al.* 1997; Davis *et al.* 1999; Silberstein *et al.* 2000; Zoppou and Knee 2000).

- Advances in numerical methods in hydrology (Short *et al.* 1995; Roberts and Zoppou 2000; Zoppou *et al.* 2000).

- Distillation of physical principles of catchment organisation (Aryal *et al.* 2000a,b; Hatton *et al.* 1995).

- Improved coupling of the surface energy balance to catchment and regional scale water balance models (Pierce *et al.* 1993; Kalma *et al.* 1995; Sivapalan *et al.* 1996a,b,c; Silberstein *et al.* 1999b,c; Shao *et al.* 2000)

- Coupling of plant growth to the energy and water balance of regions, catchments and paddocks (Hatton *et al.* 1993; Wu *et al.* 1994; Vertessy *et al.* 1996; Silberstein *et al.* 1999a; Zhang *et al.* 1996; Zhang *et al.* 1999), and a review of such models (Hook 1997).

- Application of process-based hydrological models to test scenarios of land use change (Silberstein and Sivapalan 1995; Dawes *et al.* 1997; Salama *et al.* 1999; Hairsine *et al.* 2000; Viney and Sivapalan 2000; Wang *et al.* 2000) or climate change (Viney and Sivapalan 1996).

- An emerging view on the practical constraints of process representation in cases of sparse data, with particular emphasis on a parsimonious groundwater model for scenario testing land use options for salinity control (Dawes *et al.* 2000).

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Current Research in Predicting Catchment Response *Related to Catchment Science*

- Conceptualisation of catchment function in terms that lead to descriptions of emergent properties - i.e. describe the essential features of catchments and their behaviour in quantitative terms.

- Further development and test a theory of a hydrological equilibrium between climate, soil, and vegetation, leading toward a deeper understanding of emergent catchment properties and a predictive frame-work for impact assessment.

- Develop improved methods for determining surface water balance at a regional scale for specified purposes including recharge, run-off, and drought assessment. Enhance understanding of where to locate different vegetation types within a catchment for maximum environmental benefit.

  - Investigation of drainage below existing and alternative land uses using field experimentation and farming systems modelling (APSIM) to estimate drainage over 40 years for a matrix of land use, soil type and climate.

- Comparison of these deep drainage estimates with other empirical models and measurements.
- Application of the model to investigate the potential effects of changing the mix of land uses in particular parts of the landscape, and combining hydrological and economic analyses of alternative farming systems for different parts of the landscape to find win-win situations.

- Soil parameter measurement and prediction to improved methods for measurement and prediction of relevant soil parameters to allow cost-effective parameterisation at a catchment scale. This involves using design-based sampling to ensure efficient estimation of parameters and their variability in different parts of the landscape (Bago-Maragle project). It also involves development of simplified measurement and prediction technology (eg. pedotranfer functions) to reduce the cost of parameter measurement so that greater numbers of samples can be measured to get a better idea of parameter variability (Soil Hydraulic Toolkit Project).
- Develop new numerical methods (flow and solute transport modelling) and field techniques that contribute to a better understanding of surface water - groundwater interactions in lakes and wetlands and other man-made water bodies.
- Develop new numerical modelling tools and innovative field techniques that can be applied to problems of aquifer protection and capture zone analysis, with particular emphasis on these issues in relation to the hydrology of lakes and rivers, and their interconnection with the regional aquifers.

CATCHMENT WATERLOGGING

The development of transient, perched waterlogging (particularly on duplex soils) affects crop and pasture productivity across millions of hectares of Australia. CSIRO Land and Water researchers have helped to identify the environments and conditions under which waterlogging develops, and to assess the effectiveness of remedial works in alleviating the impacts.

Since 1993, our science in this area has included:

- Assessments of the various causes of waterlogging, as an aid in understanding the uneven effectiveness of engineering design or revegetation on its control (Cox and McFarlane 1995; Hatton *et al.* 2000; Hodgson *et al.* 2000).

- Development of pedological interpretation to help predict and understand waterlogging occurrence and intensity (Cox *et al.* 1996).

- Application and testing of a drainage model (DRAINMOD) to predict waterlogging intensity and drain performance in catchments in south-western Australia. Once the soils were saturated, the model accurately predicted drain flows. However, the model could not predict flow early in the season as soils were wetting up – drains commenced flowing well before the model predicted. To accurately predict flows at these times, the highest hydraulic conductivities measured in the field (and sometimes higher) had to be used in the model. The paper (Cox *et al.* 1994) was the first to identify the importance of preferential throughflow in these landscapes.

- Development of a soil diagnostic key to help landholders decide how to best manage saline and waterlogged catchments in the Mt Lofty Ranges, South Australia (Fitzpatrick *et al.* 1994).

- Assessment of productivity impacts of waterlogging on duplex soils (Pitman 2000).

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Current Research in Catchment Waterlogging *Related to Catchment Science*

- Development of pedo-transfer functions to provide calibrated parameters to existing models that predict waterlogging.

GROUNDWATER RECHARGE ESTIMATION

Possibly the most profound hydrological change associated with land use in Australia is through groundwater recharge. More fundamentally, groundwater recharge ultimately determines resource for development. Our ability to describe and predict changes in this quantity ultimately underpin both landscape remediation and sustainable use of water resources.

Groundwater Recharge – Measurement

Australian groundwater systems are generally complex, slow, and spatially heterogeneous. Characterisation of recharge under natural or managed conditions is fraught with practical and theoretical challenges. These relate to definition of the hydrogeological conceptual model, nonstationarity of spatial and temporal processes, and slow and variable responses to changing climate or land use.

Since 1993, CLW has made significant progress toward better investigative methods and understanding of groundwater recharge:

- A review of soil physical methods for inferring deep drainage to shallow aquifer systems (Bond 1996).
- A review of hydrographic techniques for inferring recharge (Armstrong and Narayan 1998).
- A review of chemical tracer methods for inferring groundwater recharge (Cook and Herczeg 1996).
- A review of soil water tracer methods for inferring groundwater recharge (Walker 1998).
- A review of Australian recharge studies, and the development of a predictive framework for land use change recharge estimation (Petheram *et al.* 2000).

- The development of tracer techniques based on tritium and chlorine-36 for inferring diffuse recharge, and the application of these methods to Australian groundwater systems (Cook *et al.* 1994; Cook and Robinson 2000).

- The development of chemical tracers for recharge estimation (Leaney and Herczeg 1995; Chambers at al 1996; Herczeg *et al.* 1997) and their application to specific groundwater systems.

- Improved methods for inferring catchment-scale recharge and discharge from hydrographic data and terrain (Salama *et al.* 1993) or soil type (Kennett-Smith *et al.* 1994).

- A new technique for inferring groundwater recharge associated with agroforestry (Ellis *et al.* 2000a).

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Groundwater Recharge – Modelling

There are few opportunities to measure land use or climate change impacts on groundwater recharge, compared with the potential number of combinations of locale and land use. In order to provide society with come estimate of the likely impacts of land use change or remediation, we appeal to groundwater recharge modelling on occasion, recognising that in many cases this is a trans-scientific activity. The challenge has been to develop robust, parsimonious representations that sufficiently capture key processes to provide at least an indicative estimate of recharge under a specific land management scenario.

Since 1993, CLW has achieved the following in the area of groundwater recharge modelling:

- Reviews of plot scale (Walker and Zhang 2000) and catchment scale (Hatton 1998) recharge modelling, covering a range in model complexity.
- The development and application of a process-based, plot-scale model of deep drainage (Zhang *et al.* 1999b,c)
- The development, application and evaluation of a process-based, distributed parameter catchment model (TOPOG) to the problem of groundwater recharge, climate variation and land use (Green *et al.* 1997; Zhang *et al.* 1996a).
- A novel method for modelling groundwater recharge in agroforestry situations that eliminated the need for below-ground (soils) information through application of the concept of equilibrium leaf area index and robust assumptions about tree water use in water-limited environments (Ellis *et al.* 2000b).

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Current Research in Groundwater Recharge Estimation *Related to Catchment Science*

- Application of tracer techniques to estimate recharge in a variety of Australian groundwater systems including the Perth Basin, Atherton Tablelands, and the Yilgarn Block.

- Investigations to better understand the fate of deep drainage with respect to groundwater recharge.

CATCHMENT HEALTH AND ECOHYDROLOGY

Changes in catchment water balances are affected by, and in turn affect, the ecology of managed and natural plant communities. The development of the science of ecohydrology has been a strong feature of CLW's research, and has a direct and important relationship to catchment management. Related to, and inclusive of, this research is a growing theoretical paradigm of catchment health, its properties and management.

Driving much of the interest in ecohydrology and catchment health are water policy reforms aimed at providing sufficient flow or levels of water to sustain ecosystems. The definition of environmental water requirements of Australian ecosystems is an emerging research imperative.

Since 1993, CLW has achieved much in this nexus between ecology and catchment hydrology:

- Definition of the ecophysiological response of floodplain and wetland vegetation to hydrological phenomena, such as flooding, groundwater salinity, and groundwater discharge (Akeroyd *et al.* 1998; Mensforth and Walker 1996; Taylor *et al.* 1996; Slavich *et al.* 1999a,b).

- Development and testing of a theory of ecohydrological equilibrium relating vegetation cover, climate and land. This theory is aimed at reducing the complexity of process representation and the identification of emergent properties at the landscape scale (Hatton *et al.* 1997).

- Development and application of the notion of designing managed ecosystems on the basis of functional mimicry of natural systems, with an emphasis on the hydrological cycle (Hatton 1999; Hatton and Nulsen 1999).

- Development of deeper understanding of the ecohydrology of Australian systems, and the means by which we link the sciences of hydrology and ecology (Post *et al.* 1998, 2000).

- Development and application of remote sensing techniques to assess regional drought status or vegetation health and function (Held *et al.* 2000; Held and Rodriguez 2000; McVicar and Jupp 1998; McVicar and Bierwirth 2000).

- A review of the dependence of Australian ecosystems on groundwater (Hatton and Evans 1997, 1998), and the application of diverse measurement techniques to assess the likely water balance impacts of groundwater development on a set of tropical ecosystems (Cook *et al.* 1998).

- Advances in the development of catchment health as a paradigm for landscape condition, trend and management (Walker and Reuter 1996; Reuter 1998; Walker 1999, Walker *et al.* 2000).

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Current Research in Catchment Health and Ecohydrology *Related to Catchment Science*

- Development of measures, for use in monitoring catchment health, of landscape response to land use change which integrate ecohydrological processes at the catchment scale. These studies range across several eco-regions including Mediterranean, wet tropics, temperate, and semi-arid systems.
- Understanding groundwater and vegetation processes in groundwater discharge areas.
- Delineating biogeochemical processes induced by groundwater-surface water interactions.
- Assessing impacts of extreme events, including episodic recharge (Mallee and WA), flood recharge (Liverpool Plains), and impacts of flooding regime on vegetation water use and growth (using cellulose isotopes).
- Assessing stygofauna and their dependency on water quality as an indicator of hydrogeological process in catchments near Perth, WA.
- Determining environmental allocation for ecosystems that rely on the groundwater from fractured rock aquifers. Catchments include Clare Valley (SA), Atherton (Qld), and Darwin (NT).

LANDSCAPE, LANDUSE AND DRYLAND SALINITY

The salinisation of Australia's land and rivers has emerged as the most significant environmental challenge facing the nation. CSIRO Land and Water has worked in this area of science intensively over the past two decades, and much of the public awareness and policy related to salinity is founded on our work. Research has focussed on risk assessment, process description, and remedial action.

Since 1993, we have achieved the following in this area:

- Identification of the hydrological and hydrogeological controls and influences on landscape salinisation (Salama *et al.* 1993a, 1994, 1999; Salama 1997).

- New techniques for salinity risk assessment and impacts (Bui *et al.* 1996; Cook *et al.* 1997; Walker *et al.* 2000). This work collectively provides the means to map salinity risk using sparse data and the limited synoptic data (climate, geology, elevation, vegetation cover) available at regional scales.

- Identification of salinity trends and forecasting salinisation as a result of land use change (Salama *et al.* 1993b, 1993b, 1997; Pavelic *et al.* 1997a, b).

- Assessment of the role of trees in controlling salinity. This work challenged the dominant paradigm that limited tree planting would be an effective means of salinity control, and presented a more sobering picture of the extent of revegetation required to significantly reverse or even control the problem (Farrington and Salama 1996; Hatton *et al.* 2000a; Hatton 2000).

- Design and evaluation of agroforestry systems to control salinity (Lefroy and Stirzaker 1999, Stirzaker *et al.* 1999). This work included the scoping of a new land use involving phase-farming short duration woodlots with crops (Harper *et al.* 2000, Hatton *et al.* 2000b).

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Current Research in Landscape, Landuse and Dryland Salinity *Related to Catchment Science*

- Predict the impact of land use change in catchments of the MDB on stream salinities.

- Measure and model salt in irrigated catchments of the Riverine Plains, including models for predicting the impacts of land use and water management on export of salt and models and guidelines for options to store salt via disposal basins and plantations.

- Evaluate the effectiveness of deep groundwater drains on farm production and their downstream impacts due to changes in salt load, salinity and flood peaks in WA.

- Investigate and forecast likely changes to the ecologies of low-lying areas subject to salinisation in the WA Wheatbelt.

- Investigate the long-term effects of tree-planting large fractions of upland catchments with respect to salinity control.

FUTURE DIRECTIONS, SKILLS, GAPS IN KNOWLEDGE

- Defining and modelling the links between catchment water use, carbon balance (net primary productivity) and nutrient balance, to further elucidate basic constraints which set bounds on possible landscape management strategies for achieving productive, sustainable, low-leakage catchments.
- Forecasting the basin-scale response in flows and salt loads as a function of different levels of intervention, over long time scales.
- Defining the abiotic characteristics (thresholds, tolerances, frequency, volumes, levels) of surface and groundwaters associated with the maintenance of the potential ecosystems dependent on water.
- Defining the risks to supply in the face of simultaneous climate change, nonstationarity due to past management, and future land and water use options, both in terms of quantity and quality.
- Future work, which forms part of the 'Heartlands' program, to build on plot-scale modelling to include lateral linkages in a simple way using digital terrain analysis. (ie. without recreating a complex distributed-parameter model). Also, to identify in which parts of the landscape we can get away with 1-D modelling. The objectives of this work are (a) to achieve a spatial implementation of farming system and landscape process models; (b) to develop cost effective methods to measure relevant soil & regolith parameters and their variability at a catchment scale including devising landscape models for the spatial prediction of land attributes; and (c) to better understand the minimum land resource information needed for reliable landscape design and catchment hydrological analysis by developing an operational system of functional sensitivity analysis to guide field measurement programs in land resource survey, particularly for characterisation of the water-balance.
- Inferring catchment condition and trend from sparse data.
- Inferring catchment function from structure, and vice-verse.