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Hydrology and Earth System Sciences

A daily salt balance model for stream salinity generation processes following partial clearing from forest to pasture

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Abstract. We developed a coupled salt and water balance model to represent the stream salinity generation process following land use changes. The conceptual model consists of three main components with five stores: (i) Dry, Wet and Subsurface Stores, (ii) a saturated Groundwater Store and (iii) a transient Stream zone Store. The Dry and Wet Stores represent the salt and water movement in the unsaturated zone and also the near-stream dynamic saturated areas, responsible for the generation of salt flux associated with surface runoff and interflow. The unsaturated Subsurface Store represents the salt bulge and the salt fluxes. The Groundwater Store comes into play when the groundwater level is at or above the stream invert and quantifies the salt fluxes to the Stream zone Store. In the stream zone module, we consider a "free mixing" between the salt brought about by surface runoff, interflow and groundwater flow. Salt accumulation on the surface due to evaporation and its flushing by initial winter flow is also incorporated in the Stream zone Store. The salt balance model was calibrated sequentially following successful application of the water balance model. Initial salt stores were estimated from measured salt profile data. We incorporated two lumped parameters to represent the complex chemical processes like diffusion-dilution-dispersion and salt fluxes due to preferential flow. The model has performed very well in simulating stream salinity generation processes observed at Ernies and Lemon experimental catchments in south west of Western Australia. The simulated and observed stream salinity and salt loads compare very well throughout the study period with NSE of 0.7 and 0.4 for Ernies and Lemon catchment respectively. The model slightly over predicted annual stream salt load by 6.2% and 6.8%.

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1 Introduction

Stream and land salinisation is a major environmental problem occurring in many parts of the world (Abrol et al., 1988; Ghassemi et al., 1995). Stream salinity particularly affects parts of Asia, North America and Australia (Mckell et al., 1986). The salinity problem is reasonably well documented in Australia compared to other parts of the world (Hatton et al., 2002, 2003; Peck and Hatton, 2003; Halse et al., 2003). In Western Australia most of the salinity problem is associated with dry land, rain fed agriculture (known as dryland salinity) rather than irrigated agriculture.

The extent of dryland salinity in Western Australia was estimated in 1994 as 9.4% of the area cleared for agriculture (Ferdowsian et al., 1996). This represents a loss of more than 1.8 million hectares of agricultural land (State Salinity Council, 2000) with up to 8.8 million hectares at risk by 2050 (Anon, 1996). Only 44% of the State's water resources are fresh and the remaining 56% are brackish or saline (Mayer et al., 2004). Projections show that without any effective land use management, more than 3 million hectares of land will be affected by 2015, and 6 million hectares or 30% of the agricultural area will be saline when a new hydrological equilibrium between recharge and groundwater discharge to stream

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is reached (Ferdowsian et al., 1996; State Salinity Council, 2000).

Stream and land salinity in Western Australia has developed following the clearing of deep rooted, native vegetation and its replacement by shallow-rooted, annual agricultural crops and pastures (Schofield and Ruprecht, 1989; Ruprecht and Schofield, 1991). This land use change has led to an increase in groundwater recharge and rising water tables. This process has mobilised the salt stored in the unsaturated zone of the soil profile and eventually discharged to streams (Wood, 1924). The magnitude of stream salinity increase is dependent on annual rainfall and the extent and location of clearing (Schofield and Ruprecht, 1989; Mayer et al., 2004). The factors causing the land and stream salinity in Western Australia are different from other parts of the world. For example, in Queensland (Australia) salinity is caused by summer dominant rainfall, local aquifer system recharge and discharge areas are separated in space (Thornburn, 1991). Thornburn (1991) found similarity between the causes of salinity in Queensland and the Great Plains of northern United States of America (Miller et al., 1981). Stolte et al. (1997) noted that the factors affecting salinity in Western Australia were "very different" from those in the prairies of North America.

In the 1970s, a series of experimental catchments were established in the south-west of Western Australia to further understand the stream and land salinisation process following land use changes (Peck and Williamson, 1987). Catchment models were also developed to represent the hydrological processes and were successfully applied from experimental to large water resources scale. The Darling Range Catchment Model (DRCM) and the Large Scale Catchment Model (LASCAM) are the two recent examples (Mauger, 1986; Sivapalan et al., 1996; Viney et al., 2000; Viney and Sivapalan, 2001). An integrated modelling framework for the assessment of salt and water balance of a large dryland salinity affected catchment in the south-eastern part of Australia has been reported (Tuteja et al., 2003). Application of these models show that there are scope for improvement in the mathematical representation of the physical processes, particularly for the dynamic variations of the stream zone saturated areas and the mixing and distribution of salts brought about by rising groundwater to the stream zone. The limitations of the previous models were also highlighted by recent application of a fully distributed catchment model, WEC-C (Water and Environmental Consultants – Catchment) at experimental catchments. Observations show that stream salt load from these catchments has increased more than 100 times following clearing of native forest (Bari and Croton, 2000, 2002; Croton and Bari, 2001).

We developed a catchment water balance model following the "downward approach" originally suggested by Klemes (1983). The water balance model was successfully applied and tested in two experimental catchments in Western Australia (Bari and Smettem, 2006). The principal objective of this paper is coupling and testing a salinity component with the water balance model. The coupled salt and water balance model would require minimal calibration and will be used as an elementary unit in developing a regional-scale ($>1000\,\mathrm{km}^2$) catchment model.

2 The study catchments

The paired catchments, Ernies and Lemon, are located in the south west of Western Australia, some 250 km south of Perth (Fig. 1). The areas of Lemon and Ernies catchments are 344 ha and 270 ha, respectively. The catchments have Mediterranean climate, with cool, wet winters and warm to hot, dry, summers. Ernies catchment was established as forested control. The annual pan evaporation and annual rainfall for both the catchments are approximately 650 mm and 1600 mm respectively. Typically more than 80% of average annual rainfall falls in the six months from May to October. Rainfall generally exceeds pan evaporation for only four months of the year (June to September). The native forest was dominated by jarrah (*Eucalyptus marginata*). Approximately 53% of the native vegetation of the Lemon catchment was cleared in 1977 to develop a comprehensive understanding of the streamflow and salinity generation processes following land use change (Fig. 3). The cleared area of Lemon catchment was used for sheep grazing. The Lemon and Ernies catchments have broad and flat valley, with typical surface slope of about 12% and 5%, respectively. Both catchments are characterised by the presence of duricrust or sandy and gravelly superficial deposits on the surface overlying kaolinite-rich weathered material. The lateritic profile consists of two hydrologically distinct layers, the surface soil layer is typically 50–650 cm thick of high hydraulic conductivity, overlying a deep kaolinitic sandy clay 10–30 m subsoil of much lower hydraulic conductivity. The permanent groundwater system lies about 20 m below the soil surface in the forested areas.

Rainfall was recorded at the location of the gauging stations for both the catchments. Salt fall beneath forest canopy for the period 1974–1981 was measured at 5 sites in Ernies and one site in the Lemon catchment (Fig. 3). Streamflow was measured by a sharp-crested V-notch weir. Electrical conductivity of streamflow was measured by toroidal cells. Stream salinity samples were collected generally once a month. In 1972 bore networks were established at both catchments to monitor shallow and deep groundwater levels. At the Lemon catchment transects were established to measure changes in groundwater level due to clearing. A grid of groundwater monitoring bores was installed across the mouth of the catchment to establish subsurface groundwater flow. Soil profile data was collected from five sites, as representative of the hydrological provinces, in each of the catchments to estimate porosity, soil texture, bulk density, moisture content and salt storage. Pump tests were conducted to

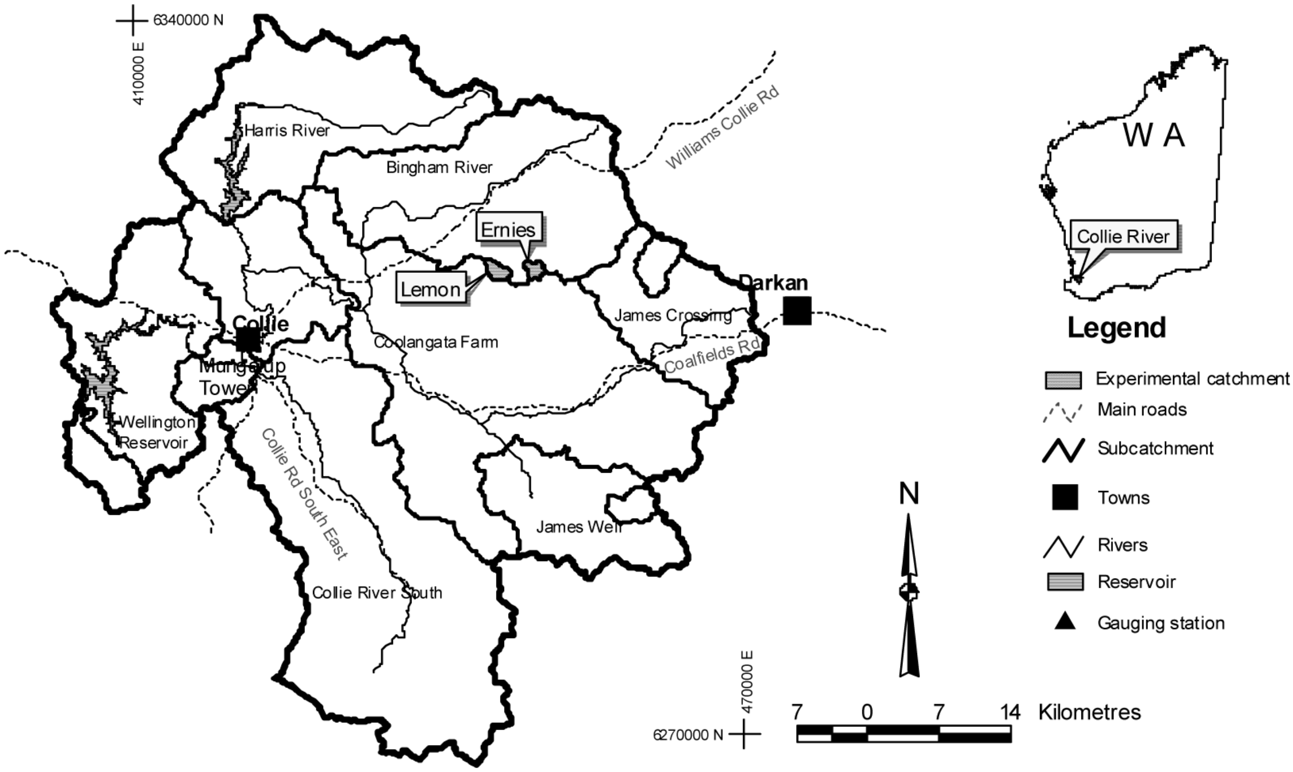

Fig. 1. Location of the experimental catchments (after Bari and Smettem, 2006).

measure hydraulic conductivity of the pallid zone (Peck and Williamson, 1987).

3 Salinity generation process

3.1 Salt fall and distribution

Salt fall on Ernies and Lemon catchments was measured at 7.8 mg L^{-1} TDS. The salinity recorded in a fully exposed gauge was generally lower than that of an under canopy gauge (Williamson et al., 1987). The principal source of salt in the soil profile is the atmospheric input originating from the ocean (Hingston and Gailitis, 1976) and increases with distance from the coast due to less flushing with lower rainfall (Stokes et al., 1980). Soil salt profile data was limited to five locations for both catchments. The salt content of the shallow highly conductive top soil is significantly less than that of the less conductive, very deep unsaturated profile, which extends to the groundwater system. Salt content of the groundwater system is generally less than that of the unsaturated zone. The soil salt storage also varies both spatially and vertically within both of the catchments. Johnston et al. (1987) classified the vertical soil salt distribution into two forms: (i) bulge profile and (ii) monotonically increasing profile. Groundwater salinity samples were collected on a monthly interval during 1974–1980 then occasionally for the rest of the monitoring period.

3.2 Recharge and salt mobilisation

Groundwater level data from the Ernies control catchment show little variation between years and lies approximately 20 m below the stream bed. There was a systematic increase in groundwater level observed at Lemon catchment due to clearing and increase in net recharge (Bari and Smettem, 2004). The vertical recharge component mobilises salt stored in the unsaturated zone and the rising groundwater dissolves it. Therefore, the groundwater salinity increases (Croton and Bari, 2001). The rate of groundwater salinity increase depends on recharge rate and salt stored in the soil profile.

3.3 Stream salinity generation

During the pre-treatment period (1974–1976) stream salinity and load of both Ernies and Lemon catchments were similar (Fig. 3). Streamflow was composed only of surface runoff and interflow components. The permanent groundwater level was 20 m below the stream bed. A substantial part of streamflow is generated by shallow interflow and most of the rainfall salt accumulates in the unsaturated zone (Ruprecht and Schofield, 1989; Bari et al., 1996). After clearing of native forest there was about 20% increase in flow components

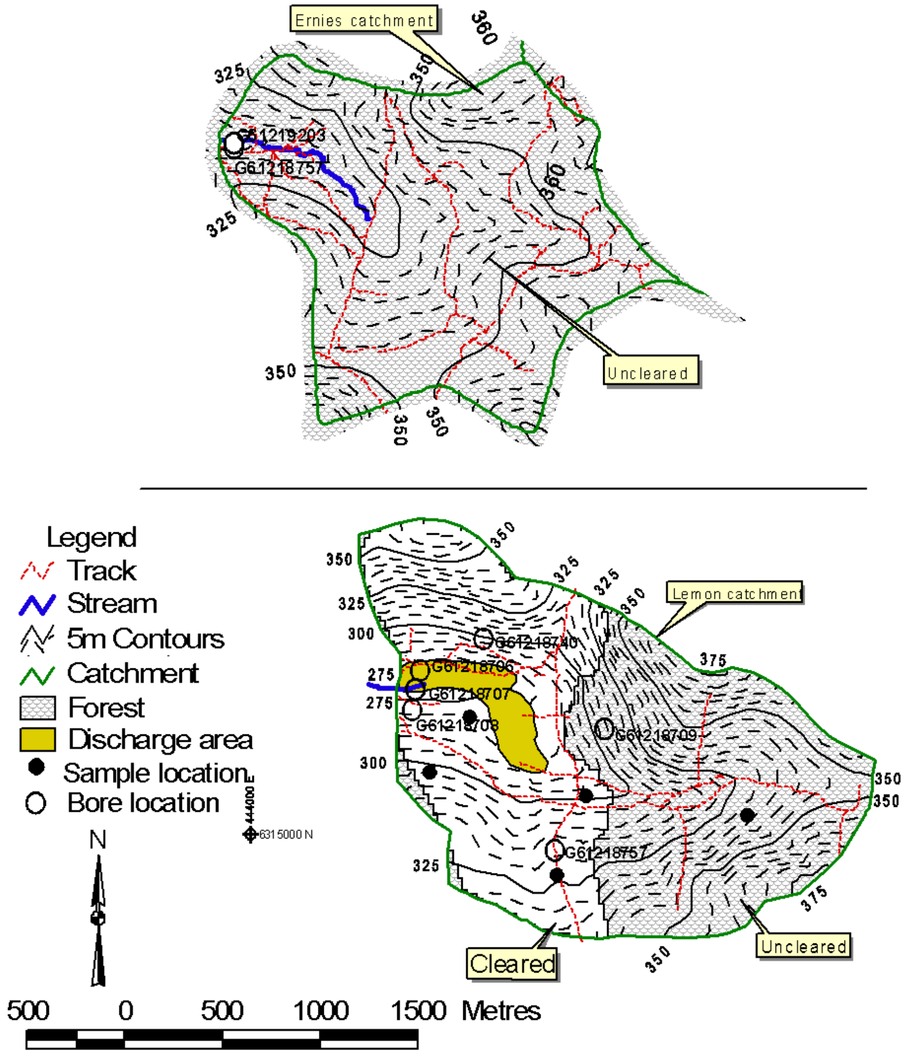

Fig. 2. Detail set up of Ernies and Lemon catchments (after Bari and Smettem, 2006).

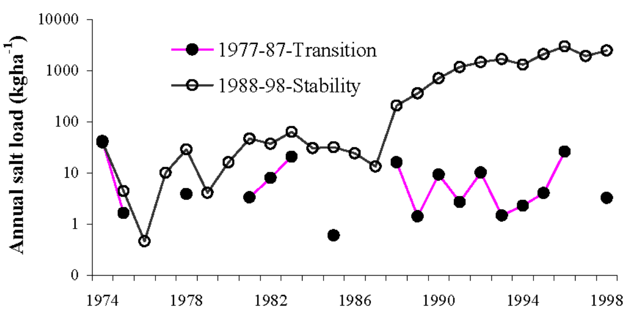

Fig. 3. Comparison of annual salt load between Ernies and Lemon catchments.

from Lemon catchment until 1987, when the groundwater system had risen to reach the stream invert. There was significant reduction in the interception and transpiration compared to the Ernies control catchment (Table 1). The water balance model predicted a significant increase in groundwater recharge and moisture content in the unsaturated soil profile (Bari and Smettem, 2006). As there is very little salt storage in the highly conductive top soil, stream salinity was in the order of 100–150 mg L^{-1} TDS. Once a small groundwater discharge area appeared in 1987, the annual stream salinity increased from 115 mg L^{-1} TDS to 2000 mg L^{-1} TDS, when the catchment reached a new equilibrium. The water balance model predicted that there was major changes in flow generation processes – surface runoff and baseflow components increased significantly due to an increase in stream zone saturated areas (Bari and Smettem, 2006). The salt discharge increased about 80 fold (Fig. 3) mainly due to the discharge of highly saline (∼5000 mg L^{-1} TDS) groundwater to the stream (Bari and Smettem, 2004). Analyses of daily stream salinity during 1987–1998 show a significant increase

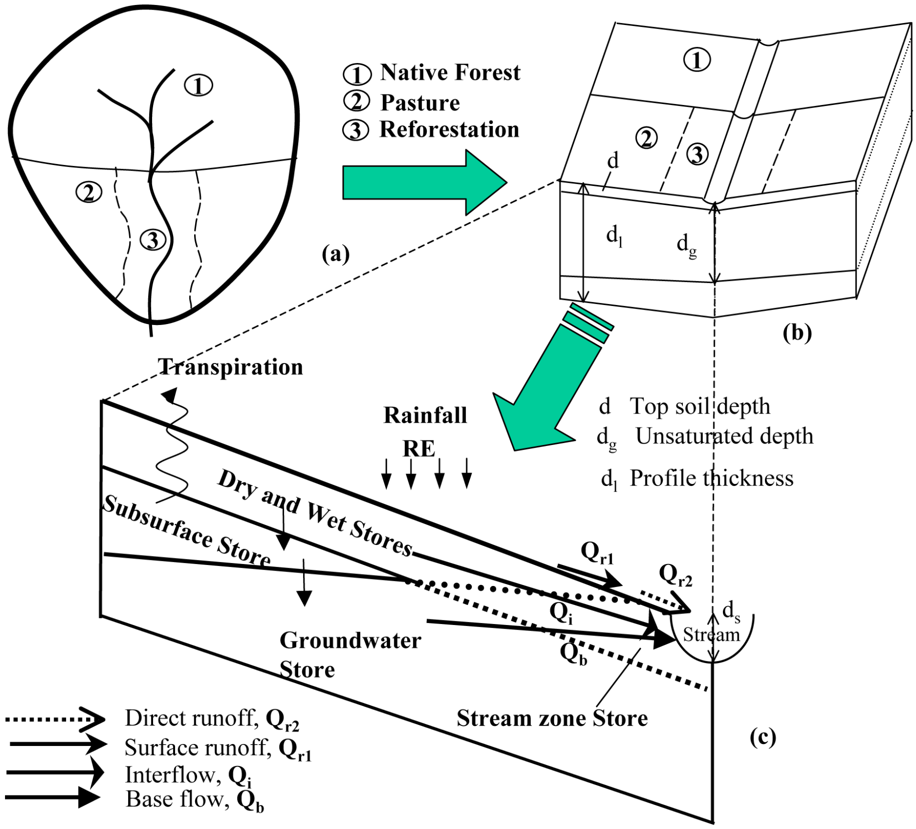

Fig. 4. Schematic diagram of five-store model, **(a)** a hypothetical catchment, **(b)** open book representation, **(c)** five stores.

in salinity during the early winter flow, due to evaporation and flushing of salts accumulated in the stream zone.

4 Model description

We introduced a salinity component into the daily water balance model (Bari and Smettem, 2006). The structure of the coupled model remained unchanged (Fig. 4) from the water balance model in terms of stores and fluxes between them. The water balance model includes evapotranspiration, surface runoff and interflow, percolation and recharge to the deep groundwater. The model also includes the dynamic variation of the stream-zone saturated areas and discharge (if any) from the deep groundwater system. The water balance model has five stores: (i) Dry, Wet and Subsurface Stores, (ii) Groundwater Store and (iii) transient Stream zone Store (Fig. 5).

Evapotranspiration comprises three components: interception, plant transpiration and soil evaporation. Interception is represented by a canopy store, which is dependent on the Leaf Area Index of the vegetation. The rest of the rainfall reaches the soil surface and either infiltrates or generates runoff. Rainfall salt is intercepted on the plant leaves but then washed onto the soil surface in the subsequent events. Plant transpiration is modelled as a function of the Leaf Area Index, the relative root volume in all five stores (Fig. 5), the moisture content and the potential energy (pan evaporation). Soil evaporation takes place from the Dry, Wet and the Stream zone stores. Surface runoff requires rainfall intensity to exceed the infiltration capacity of (saturated) soils and this is rare in Western Australia. It is dependent upon the water content of the Wet Store and the variably contributing saturated areas along the stream zone (Fig. 5). Where part of the stream zone is saturated by the presence of the permanent groundwater system, additional surface runoff is generated. Interflow is the contribution of shallow, intermittent groundwater after rainfall recharge. It is a function of the lateral hydraulic conductivity of the topsoil, and the water content of the Wet Store. Percolation is the amount of vertical water flow between the highly conductive topsoil to the less conductive Subsurface Store (Fig. 5). It is controlled by the vertical conductivity, the water content in the Wet Store and the soil moisture deficit in the Subsurface Store. Most of the percolated water is transpired by the deep-rooted trees and very little reaches the Groundwater Store. Recharge to the Groundwater Store comprises both matrix and preferential flow. Baseflow is the contribution of the (permanent) groundwater system to streamflow. It ensues where the Groundwater Store connects to the stream bed to form the Stream zone

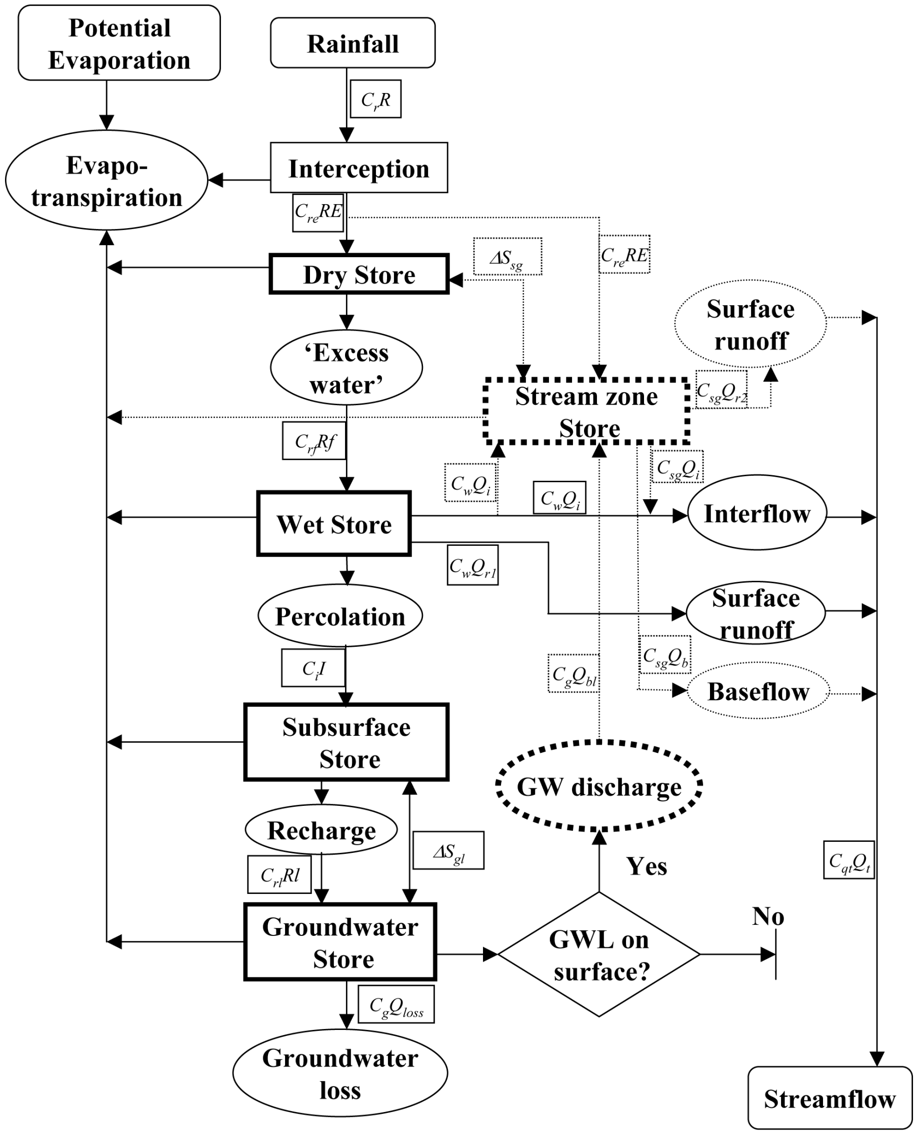

Fig. 5. Schematic representation of the water and salt balance model.

Table 1. Water balance components (mm) of Lemon and Ernies catchments.

Water balance components	Ernies catchment Pretreatment 1974–1976	Ernies catchment Transitional 1977–1995	Ernies catchment Stability 1996–1998	Lemon catchment Pretreatment 1974–1976	Lemon catchment Transitional 1977–1995	Lemon catchment Stability 1996–1998
Rainfall	2121	13 440	2237	2121	13 440	2237
Interception	329	2241	361	329	1290	211
Transpiration	1863	10 950	1755	1727	8622	1437
Soil evaporation	46	287	46	44	837	147
Surface runoff	9	54	12	43	428	122
Interflow	49	59	34	69	669	215
Baseflow	0	0	0	0	80	60
Loss through base	1	8	1	1	23	5
Storage change	−176	−159	27	−92	1491	40

Store. It is a function of the lateral hydraulic conductivity of the aquifer, hydraulic gradient and discharge area along the stream.

4.1 Salt interception

Rainfall salt intercepted by the plant canopies is washed off to the ground by the next rainfall event. Salt fall and salt storage (S_r) on the canopy depends upon rainfall (R) and its salinity (C_r). It can be calculated as:

$$S_r(t+1) = C_r(t,t+1)R(t,t+1) + S_r(t) \quad (1)$$

Following evaporation of intercepted water, the concentration of effective rainfall (C_{re}) increases. Salinity of the effective rainfall and salt fall on the ground (S_{re}) can be calculated as:

$$C_{re} = \frac{S_r}{RE} \quad \text{if} \quad RE > 0 \quad (2a)$$

$$C_{re} = 0 \quad \text{if} \quad RE = 0 \quad (2b)$$

$$S_{re} = C_{re}RE \quad (2c)$$

4.2 Unsaturated salt stores

4.2.1 Salt in the Dry Store

The Dry Store is conceived to receive rainfall salt and represents most of the salt contained in the highly conductive, shallow, top soil. We assume complete mixing of salt and water within the store and represent the unsaturated or "immobile" state of solute. When the moisture content of part of the catchment exceeds field capacity (θ_f), this store releases water and salt to the Wet Store (Bari and Smettem, 2006). Salt concentration of the Dry Store is:

$$C_d = \frac{S_d}{W_d} \quad (3)$$

After effective rainfall, part is released from the Dry Store to the Wet Store. The concentration of the released salt (C_{rf}) depends upon chemical processes like dilution-diffusion-advection-dispersion-convection. We introduced a lumped parameter (C_u) to represent these processes. Therefore, the concentration (C_{rf}) of the "excess water" (Rf) and the salt released from Dry Store to Wet Store (S_{rf}) can be expressed as:

$$C_{rf} = C_u C_d \quad (4a)$$

$$S_{rf} = C_{rf} Rf \quad (4b)$$

When the groundwater level rises and intersects the stream bed the Stream zone Store comes into play. The Dry Store loses salt to the Stream zone Store (ΔS_{sg}) when the saturated area expands and gains salt when that contracts. This can be calculated as:

$$\Delta S_{sg} = C_d \Delta W_{sg} \quad \text{if} \quad \Delta d_g < 0 \quad (5a)$$

$$\Delta S_{sg} = C_{sg} \Delta W_{sg} \quad \text{if} \quad \Delta d_g > 0 \quad (5b)$$

The Dry Store Salt update at any time (t+1) is:

$$S_d(t+1) = S_d(t) + S_{re}(t,t+1) - S_{rf}(t,t+1) - \Delta S_{sg}(t,t+1) \quad (6)$$

4.2.2 Salt in the Wet Store

The Wet Store represents salt in the water that is free to move vertically and laterally. The Wet Store represents the dynamically variable saturated areas, predominantly observed in the near-surface stream zone. Salt concentration (C_w) of the Wet Store is dependent on the amount of salt (S_w) and water (W_w) present at a particular time:

$$C_w = \frac{S_w}{W_w} \quad (7)$$

The surface runoff is generated as saturation excess (Q_{r1}) and from the "impervious" groundwater induced saturated area (Q_{r2}). Surface runoff (Q_{r2}) brings rainfall salt to the Stream zone Store and contributes salt to the stream (Eq. 20). If we assume free mixing, the concentrations of the surface runoff (Q_{r1}) and interflow (Q_i) are identical to the Wet Store concentration (C_w). Therefore, salt transported to the stream by surface runoff (Q_{r1}) and interflow are:

$$S_{qr1} = C_w Q_{r1} \quad (8)$$

$$S_{qi} = C_w Q_i \quad (9)$$

The percolation (I) from the Wet Store to the Subsurface Store includes preferential flow. The salt concentration of the percolated water is less than that of the Wet Store and is represented by introducing a parameter (C). Therefore, the total salt transported from the top soil to the subsurface unsaturated profile (S_i) and its concentration (C_i) are:

$$C_i = CC_w \quad (10a)$$

$$S_i = C_i I \quad (10b)$$

Under a native forest scenario salt content of the Wet Store should remain stable for a long period of simulation. The salt balance of the Wet Store can be expressed as:

$$S_w(t+1) = S_w(t) + S_{rf}(t,t+1) - S_{qr1}(t,t+1) - S_{qi}(t,t+1) - S_i(t,t+1) \quad (11)$$

4.2.3 Salt in the Subsurface Store

The Subsurface Store represents the salt bulge naturally present in the unsaturated soil profile. The salt concentration of this store (C_l) can be expressed as:

$$C_l = \frac{S_l}{W_l} \quad (12)$$

The Subsurface Store loses salt to the groundwater system by recharge (Rl), as preferential and matrix flow. We assume that the concentration of the recharge salt can be expressed as a function of salt concentration of the Subsurface Store and the parameter used for the Dry Store. Therefore the salinity (C_{rl}) and salt load of recharge (S_{rl}) can be expressed as:

$$C_{rl} = C_u C_l \tag{13a}$$

$$S_{rl} = C_{rl} Rl \tag{13b}$$

The Subsurface Store exchanges salt to the Groundwater Store (ΔS_{gl}) due to the fluctuation of the groundwater level (Δd_g) and can be quantified as:

$$\Delta S_{gl} = \Delta W_{gl} C_l, \quad \text{if} \quad \Delta d_g \leq 0 \tag{14a}$$

$$\Delta S_{gl} = \Delta W_{gl} C_g, \quad \text{if} \quad \Delta d_g \geq 0 \tag{14b}$$

The salt balance of the Sub-surface Store at time (t+1) is given as:

$$S_l(t+1) = S_l(t) + S_i(t, t+1) - S_{rl}(t, t+1) - \Delta S_{gl}(t, t+1) \tag{15}$$

4.3 Salt in the Groundwater Store

The salt present in the Groundwater Store (S_g) is initially estimated from salinity of the observation bores or salt storage data and the concentration can be expressed as:

$$C_g = \frac{S_g}{W_g} \tag{16}$$

The Groundwater Store contributes salt (S_{qbl}) to the stream when the groundwater system intersects the stream bed. This store can also lose salt (S_{qlo}) to the down stream groundwater system, which is not recorded by the gauging station. Therefore, loss of salt from the Groundwater Store below the gauge and salt contribution to the stream zone can be expressed as:

$$S_{qbl} = C_g Q_{bl} \tag{17}$$

$$S_{qlo} = C_g Q_{\text{loss}} \tag{18}$$

When the groundwater level fluctuates, the Groundwater Store exchanges salt to the Subsurface Store (Eq. 14). The Groundwater Store salt balance can expressed as:

$$S_g(t+1) = S_g(t) + S_{rl}(t, t+1) - S_{qlo}(t, t+1) - S_{qbl}(t, t+1) + \Delta S_{gl}(t, t+1) \tag{19}$$

4.4 Salt in the Stream zone Store

The Stream zone salt Store is transient and is created by the deep groundwater system only. When the groundwater level is at or above the stream bed salt storage is controlled by the surface runoff, interflow and baseflow. Soil evaporation also takes place from this store, which eventually increases the salt concentration and in the dry months leaves salt on the surface (surface salt crusting). When the Stream zone Store contracts/expands it exchanges salt with the Dry Store. Salt is brought to this store by rain, interflow (from the Wet Store) and baseflow (from the Groundwater Store) components. We calculate the salt balance of this store sequentially, firstly for surface runoff and then interflow and baseflow respectively. Surface runoff (Q_r) consists of runoff generated from the transient stream zone saturated areas (Q_{r1}) and from groundwater induced saturated areas (Q_{r2}). Both of these components mix with the salt in the stream zone to some extent and bring it to stream. For simplicity we assume that Q_{r1} does not mix with the salt in the stream zone while Q_{r2} is well mixed. Salt contribution (S_{qr2}) by Q_{r2}, its concentration (C_{qr2}) and salt balance of the store can be calculated as:

$$C_{qr2} = \frac{S_{sg} + C_{re} Q_{r2}}{W_{sg} + Q_{r2}} \tag{20a}$$

$$S_{qr2} = C_{qr2} Q_{r2} \tag{20b}$$

$$S_{sg}(t+1) = S_{sg}(t) + C_{re}(t, t+1) Q_{r2}(t, t+1) - S_{qr2}(t, t+1) \tag{20c}$$

Similar to the surface runoff Q_{r2}, salt storage and concentration are sequentially updated due to interflow and baseflow. There is also exchange of salt between the Stream zone Store and the Dry Store, due to contraction/expansion of the stream zone saturated area (Eq. 5). Therefore, the salt balance of the Stream zone Store after each time step can be expressed as:

$$S_{sg}(t+1) = S_{sg}(t) + \Delta S_{sg}(t, t+1) \tag{21}$$

4.5 Stream salt load

Stream salt load is the sum of surface runoff interflow and baseflow salt components. The total salt flow to stream (S_{qt}) and salinity (C_{qt}) can be expressed as:

$$S_{qt} = S_{qr1} + S_{qr2} + S_{qi} + S_{qb} \tag{22a}$$

$$C_{qt} = \frac{S_{qt}}{Q_t} \tag{22b}$$

5 Model calibration and data requirements

The coupled water and salt balance model is calibrated sequentially. At first the parameters related to water balance are calibrated (Bari and Smettem, 2006), and then the other parameters associated with the salt balance. The salt balance model has two parameters. The first one (C_u) is related to salt release from Dry Store to the Wet Store (Fig. 5). This single parameter lumps the transport and mixing processes like convection, advection, dispersion, diffusion and dilution. This parameter indirectly controls the concentration of the Wet Store. The indicative salinity of the Wet Store can be estimated from the salinity data observed from the shallow bores. The other parameter (C) controls salt concentration of the percolation water and represents the vertical advection, probably due to the presence of preferred pathways in the unsaturated soil profile (Johnston et al., 1987). These two parameters were calibrated through trial and error. Under a native forest scenario the calibrated values of these two parameters should be such that the salt storage of the Dry and Wet Stores remains stable under long term simulations, and that the predicted salinity should reasonably match with the observed data.

In the coupled salt and water balance model Ernies catchment was represented as one subcatchment. To represent clearing of forest, Lemon catchment was divided into two subcatchments with 53% and 47% of the area respectively (Fig. 2). To represent clearing, only the rooting depth and LAI of one subcatchment were changed from trees to pasture values in 1977 when clearing took place.

The first five-year's stream salinity data of Ernies catchment and data up to 1987 of Lemon catchment was used for the coupled model calibration. The rest of the observed data was used for model verification. We took the arithmetic average of the observed salt fall data and it remained constant over time for both catchments. The initial conditions of the five connecting Stores are estimated from observed soil salt profile data. Soil salt profiles were taken from five boreholes, located in the stream zone, mid slope and up slope at each of the catchments. Salt storage ranged from less than 1 kg m^{-3} to 7 kg m^{-3}. Salt content of the Subsurface Store was estimated at 2.5 kg m^{-3} for both catchments. Salt concentration of the Groundwater Store was taken as the average salinity of the groundwater observation bores. At the Lemon catchment salinity of the permanent groundwater system was measured in 72 observation bores and was showing a large variation, ranging from 1000 to just less than 6000 mg L^{-1} TDS. This large variation may partially be due to the presence of localised preferred pathway recharge (Johnston, 1987) and different hydraulic properties of the aquifer. We assumed an initial average Groundwater Store concentration of 4000 mg L^{-1} TDS. At the Ernies catchment, groundwater salinity was monitored in 21 bores and ranged from 2500 mg L^{-1} TDS to 8000 mg L^{-1} TDS. An initial mean salinity of 5000 mg L^{-1} TDS for the Groundwater Store was adopted for modelling.

6 Model application and testing

6.1 Salinity variations in different stores

In the south west of Western Australia, salinity observed in shallow bores (less than 2.5 m deep) is generally fresh (<500 mg L^{-1} TDS) while the groundwater level remains below the stream bed. Similar results were also obtained from Lemon and Ernies catchments. At Ernies catchment, shallow bores located in the dynamically contributing saturated area exhibit salinity variations ranging from 150 mg L^{-1} TDS to 400 mg L^{-1} TDS. The measured salt content of the shallow top soil ranged between 2.5 mg mm^{-1} to 4.5 mg mm^{-1}. The predicted salt content of both the Dry Store of Ernies catchment was within that range and remained stable during the study period (Fig. 6a). The salt content of the Wet Store was also stable. The predicted salinity of the stream zone saturated area (Stream zone Store) has similar range to the salinity observed in the shallow bores located along the stream lines (Fig. 6b).

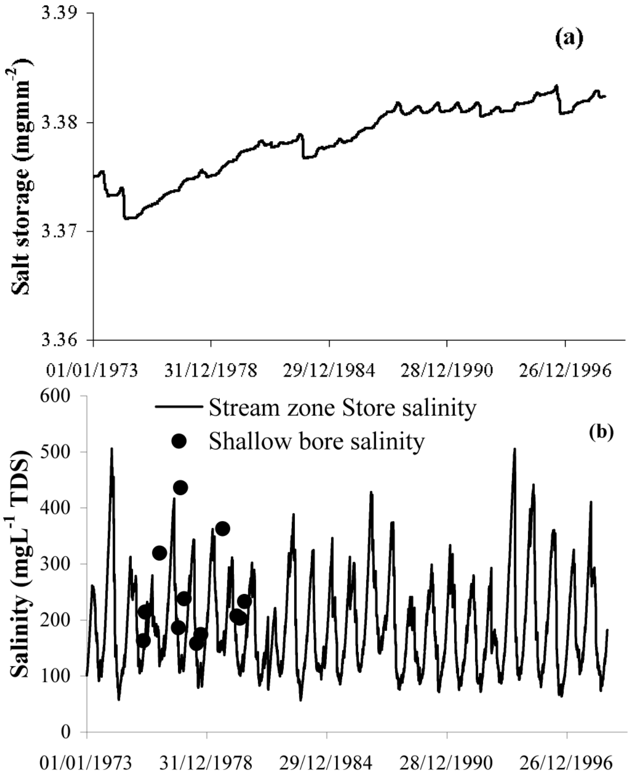

Fig. 6. Ernies catchment **(a)** salt in the Dry Store, and **(b)** salinity of the Wet Store.

The salt storage of the Dry Store of Lemon started to decrease when it was cleared in 1977. When the groundwater system reached the surface the salt content of the Dry Store started increasing again. The increase in salt content was due to the existence of the Stream zone Store with very high salinity, similar to the Groundwater Store. When the permanent groundwater level was below the stream invert, the shallow intermittent saturated area was present only in the wet period of the year when streamflow was generated (Bari and Smettem, 2004, 2006; Bari et al., 2005). Salinity of the stream zone saturated areas was generally fresh, less than 300 mg L^{-1} TDS. There was dramatic increase in salinity when the groundwater reached the surface in 1987. The model represented this process very well. For example, one shallow bore, located in the lower part of the stream zone of Lemon catchment, recorded salinity in the order of

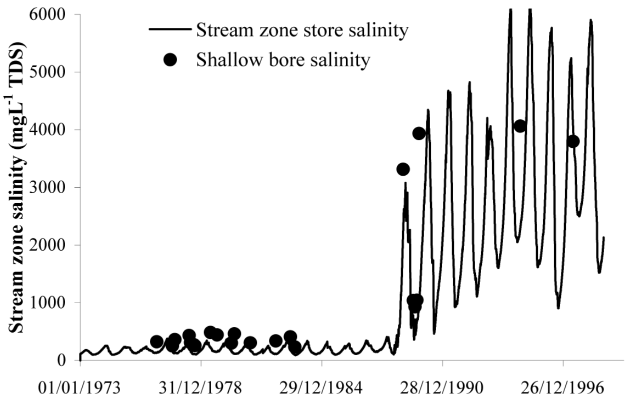

Fig. 7. Salinity at the saturated area of Lemon catchment.

$250\,\mathrm{mg\,L^{-1}}$ TDS. Since 1987 the salinity recorded in the same bore was in excess of $4000\,\mathrm{mg\,L^{-1}}$ TDS, mainly due to the contribution of the groundwater system. The model also successfully predicted similar salinity of the saturated areas of Lemon catchment (Fig. 7).

6.2 Stream salinity and salt load

The salt model was applied on a daily time step for the whole 27-year simulation period. In most of the years before and after clearing, modelled streamflow, salinity and salt load matched the observed data reasonably well for both catchments.

6.2.1 Daily salinity

The Ernies catchment exhibited average flow in 1990. The observed and simulated daily streamflow hydrographs were very similar. As the permanent groundwater system was far below the stream, there was no contribution of groundwater salt to the stream. The predicted salinity was slightly lower than observed (Fig. 8a). The observed and predicted stream salt loads were well matched, except during the recession periods, when the predicted load was slightly lower than recorded (Fig. 8b). In 1996, Ernies catchment received a particularly large annual rainfall of 880 mm. Streamflow started some time in July, increased during the high-rainfall winter months, and dried out by November. The model successfully represented the flow and salinity generation processes over this period. The observed daily stream salinity was reasonably stable at around $85\,\mathrm{mg\,L^{-1}}$ TDS (Fig. 9a). The predicted salinity was slightly smaller than the observed salinity but the overall trend was very similar. The model accurately estimated the stream salt load, including the peaks and recession (Fig. 9b).

The Lemon catchment produced the lowest flow on record in 1979, just two years after clearing. There was an immediate increase in stream salinity, in the order of $20\,\mathrm{mg\,L^{-1}}$ TDS, following clearing. The observed daily salinity was about $100\,\mathrm{mg\,L^{-1}}$ TDS when the stream started to flow in July (Fig. 10a). The stream salinity systematically increased, particularly during the recession period, to $180\,\mathrm{mg\,L^{-1}}$ TDS in October, then slightly decreased during the storm events. The model reliably represented this salinity generation process. As the modelled streamflow was slightly higher (particularly the peak flow), the peak salt discharge was also higher than observed (Fig. 10b). In 1984, the Lemon catchment received average-annual rainfall, when the permanent groundwater system was a few metres below the stream bed (Bari and Smettem, 2006). A total of 25 mm of streamflow was recorded whereas the control Ernies catchment recorded no flow. The predicted stream salinity was about $20\,\mathrm{mg\,L^{-1}}$ TDS lower than observed at the onset of winter rainfall, but matched well during the period of July to November. The predicted stream salt load was in excellent agreement with the observed values. As the groundwater system rose to the surface the stream became perennial in 1990. During dry months (November to May), when only the baseflow was dominant, the observed daily stream salinity was in excess of $2500\,\mathrm{mg\,L^{-1}}$ TDS. The model was able to predict this reasonably well, though initially the modelled salinity was slightly higher (Fig. 11a). During May to October, the

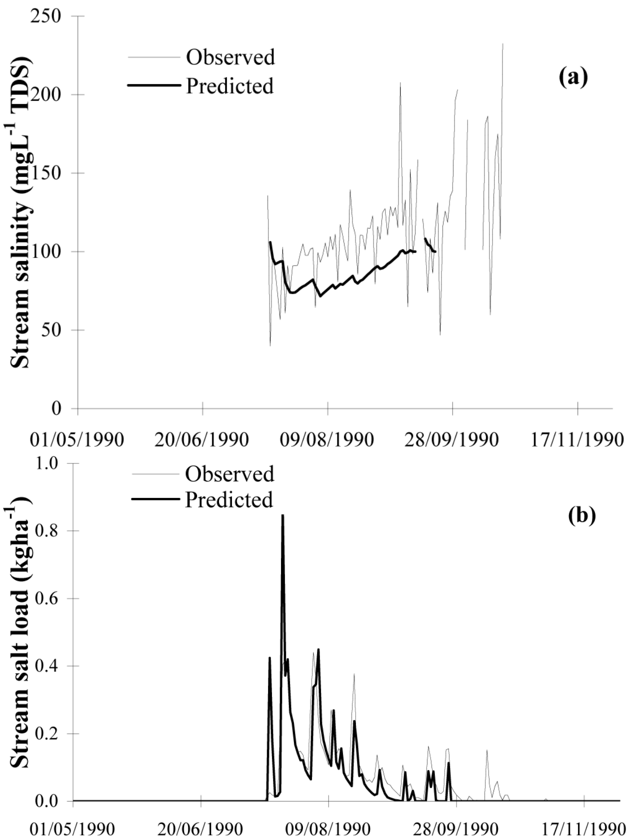

Fig. 8. Actual and predicted stream **(a)** salinity and **(b)** salt load for 1990 – Ernies catchment.

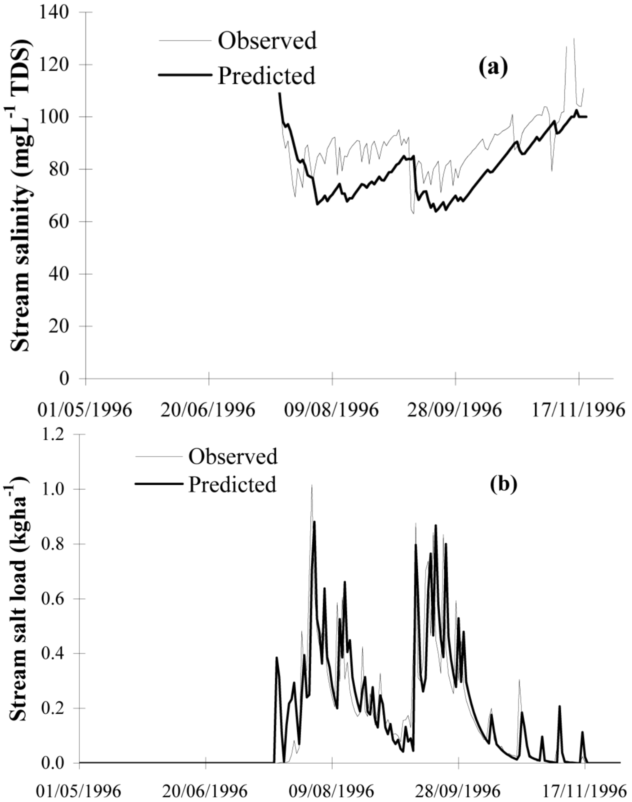

Fig. 9. Actual and predicted stream **(a)** salinity and **(b)** salt load for 1996 – Ernies catchment.

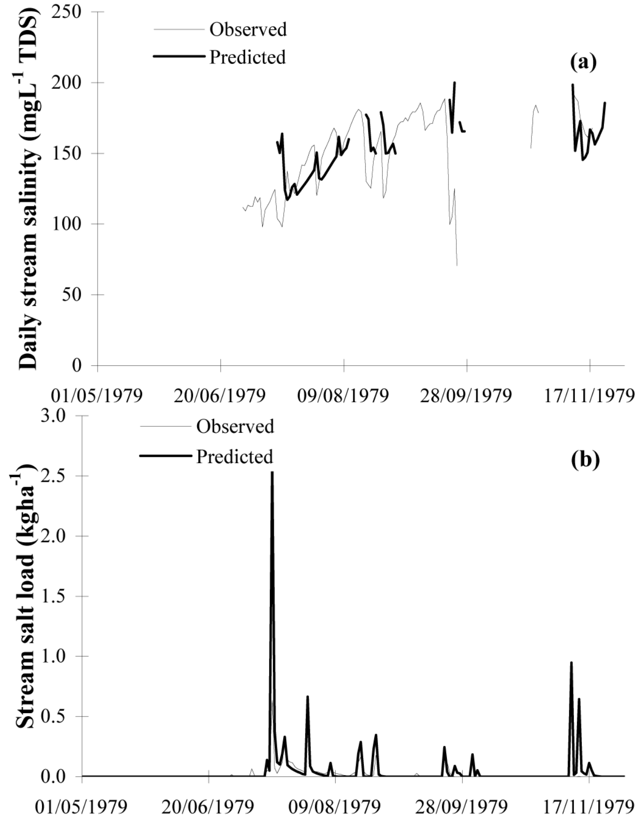

Fig. 10. Actual and predicted stream **(a)** salinity and **(b)** salt load for 1979 – Lemon catchment.

predicted daily stream salinity was reasonably well matched, but slightly lower during October to December. The predicted salt load was in close agreement with the observed salt load, with the exception of some peaks (Fig. 11b). In some of the years, matching between the observed and predicted daily stream salinity was poor, probably due to evaporation and salt accumulation and flushing from the stream zone. However, in terms of salt load, the difference between the observed and predicted salt load was acceptable.

A set of statistical criteria was defined for measuring the agreement between the predicted and observed daily salinity and salt load for both the catchments. These criteria include: (a) Nash-Sutcliffe Efficiency (E^2), (b) Correlation Coefficient (CC), and (c) Overall salt balance (E) (Table 2). The Nash-Sutcliffe Efficiency for the Ernies catchment was 0.76 and 0.44, respectively, for the calibration and verification periods. The Correlation Coefficients for both the calibration and verification period were satisfactory. The predicted annual salt load at the Ernies catchment was 3% lower and 11% higher than observed during the calibration and verification periods respectively (Table 2). At the Lemon catchment Correlation Coefficient was low during the calibration period, probably due to over-prediction of daily salt load, and improved siginificantly during the verification period (Table 2).

Table 2. Goodness of fit for daily stream salinity simulations.

Measure of fit	Calibration		Verification		Overall	
	Ernies	Lemon	Ernies	Lemon	Ernies	Lemon
E	−0.03	0.56	0.11	0.05	0.07	0.07
E^2	0.83	0.43	0.61	0.27	0.71	0.41
CC	0.92	0.27	0.78	0.65	0.84	0.72

Values of all the statistical criteria improved significantly for the monthly stream salt load (Bari and Smettem, 2005a).

6.2.2 Monthly salinity

At Ernies catchment, the model was able to predict salt loads well. A satisfactory relationship (R^2=0.91) between the observed and predicted monthly salt load was observed (Fig. 12a). At Lemon catchment, during the period of 1974–1986, when monthly stream salinity was less than 200 mg L^{-1} TDS, observed and predicted monthly salt loads were reasonably matched. During the period when the groundwater system was already at the stream invert, the model over predicted the salt load of the dry summer months

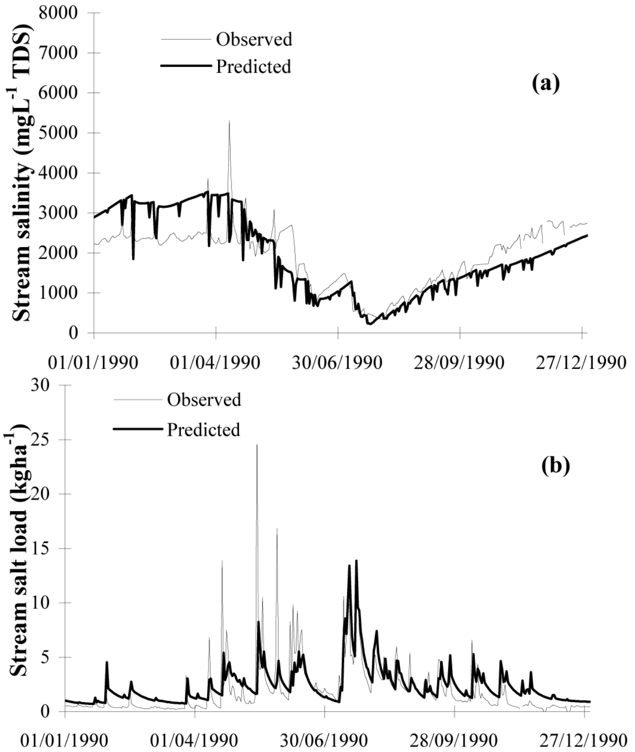

Fig. 11. Actual and predicted stream **(a)** salinity and **(b)** salt load 1990 – Lemon catchment.

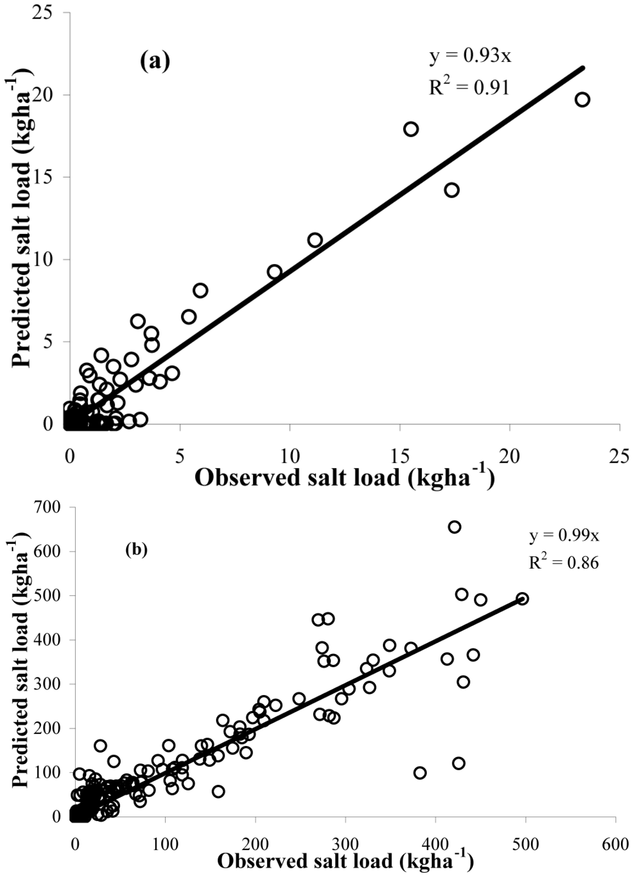

Fig. 12. Monthly stream salt load relationships – **(a)** Ernies, **(b)** Lemon catchments.

Table 3. Salt balance components (kg/ha) of Lemon and Ernies catchments.

Component	Sub-component	Lemon	Ernies
Rainfall	Rainfall	1592	1592
Storage change	Dry	−171	74
	Wet	−8	−63
	Subsurface	−207 640	470
	Groundwater	188 696	660
	Stream zone	1843	0
	Loss through base	819	281
Streamflow	Surface runoff	4435	67
	Interflow	9641	104
	Baseflow	3977	0
Mass balance		0	−1

on a few occasions. Throughout the study period, the predicted and observed monthly stream salt load generally had a good agreement (Fig. 12b).

6.2.3 Annual salinity and load

An excellent agreement between the observed and predicted annual stream salinity and salt load was observed at Ernies catchment. In 1983, the model slightly over predicted the stream salt load (Fig. 13a), which may be explained by the higher prediction of stream salinity (in excess of 20 mg L^{-1} TDS). The model also poorly predicted the annual load for 1988, when the catchment experienced two consecutive no-flow years. There is some evidence that the model slightly over predicted the salt load of some of the low flow years, although a very high correlation (R^2=0.95) was obtained (Fig. 13b). The observed and predicted salt volumes were 160 kg ha^{-1} and 171 kg ha^{-1}, respectively, resulting in an over prediction of 7%. The Ernies catchment was receiving more salt than it was discharging, resulting in a salt output to input ratio of 0.12. Therefore, the catchment salt storage also increased by 860 kg ha^{-1} (Table 3). Most of the salt accumulation was in the Subsurface and Groundwater Stores. However the Dry and Wet Store volumes of Lemon catchment was reduced due to the development of stream zone salt store (Table 3).

During 1987–1998, when the groundwater system of Lemon catchment was at the surface, the model slightly over predicted the annual load in some of the years. The Subsurface Store lost large volume of salt to the Groundwater Store due to recharge and rise in groundwater level (Table 3).

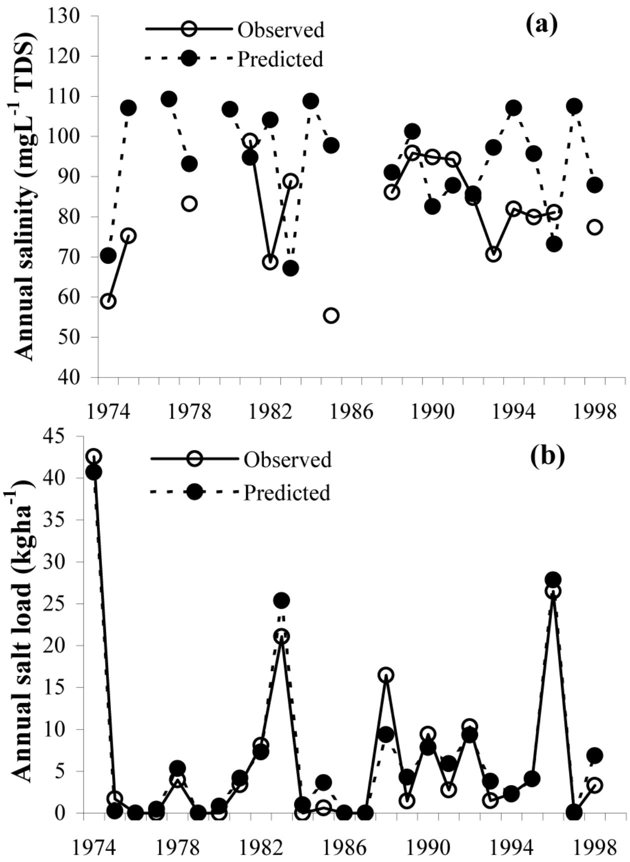

Fig. 13. Actual and predicted annual stream **(a)** salinity and **(b)** salt load – Ernies catchment.

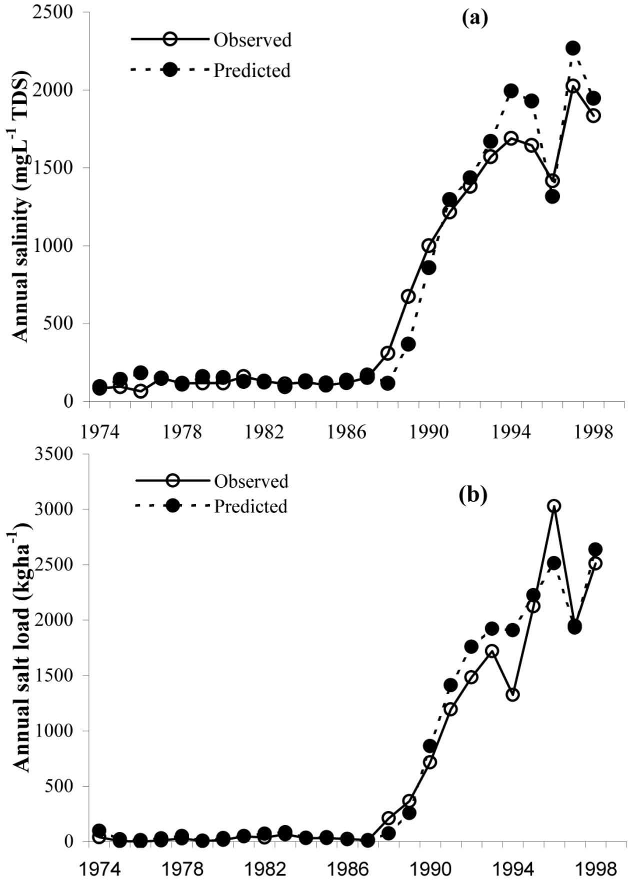

Fig. 14. Actual and predicted annual stream **(a)** salinity and **(b)** salt load – Lemon catchment.

The modelled salinity was reasonable for the whole period of study (Fig. 14a). The relationship between the observed and predicted salt load and salinity were very strong (Fig. 14b). During the study period, total observed and predicted salt discharge from the catchment was 16 982 kg ha^{-1} and 18 053 kg ha^{-1}, respectively, representing a 6% over prediction. The salt output to input ratio changed from less than one in the 1980s to in excess of 30 in the 1990s. This is also evident in the catchment salt storage, which started diminishing in the 1990s.

7 General discussion

Estimates of Subsurface and Groundwater salt Stores were limited to salt profiles taken from five locations from each of the catchments. The representation of salt content in the regolith could be improved with more data, particularly in the stream zone. The salt content of the subsurface unsaturated zone generally correlates with mean annual rainfall (Stokes et al., 1980). The initial salt content of the Subsurafce Store correlated well with the regional estimate. Initially the groundwater salinity varied across the catchments, from less than 1000 mg L^{-1} TDS to in excess of 6000 mg L^{-1} TDS. Most of the bores were slotted over the bottom three metres only. Therefore, it was not possible to accurately monitor the increase in groundwater salinity following mobilisation of the salt store by groundwater rise. Most of the groundwater observation bores show some increase in salinity, indicating mobilization and dissolution of salt from the unsaturated profile. The model predicted a systematic increase in salinity of the Groundwater Store of Lemon catchment following the rise in groundwater level. Once the groundwater level has been stabilized, it may contribute more salt to the stream than is received by the recharge component. Therefore the salinity of the Groundwater Store may have a gradual decline over a long period of time. A similar result was also predicted by Hatton et al. (2002).

Since 1987, there has been a dramatic increase in stream salinity at Lemon catchment, predominantly due to the onset of groundwater flow to the stream. During the low-flow period of the year, when mainly the baseflow component was active, the modelled and observed daily salinity was not well matched, particularly during the period when surface salt was flushed out by storm events. The salt accumulation and flushing from the stream zone are attributed to: (a) the magnitude and location of clearing, (b) groundwater table during the previous summer and capillary rise, and (c) summer streamflow and magnitude of early winter flows (Loh and Stokes, 1981). That means the accumulation of salts on the surface due to soil evaporation, and its dilution and flushing by the surface runoff, is not well simulated by the model. However, this has a negligible effect on the overall salt balance of the catchment.

Sensitivity analysis was performed using key parameters. It show that the relationship between the moisture content and lateral hydraulic conductivity (ia) is the most sensitive parameter. Reduction in calibrated value by 20% increases the daily streamflow, reduces the salt load and salinity. The daily peakflow and interflow components increased significantly and daily salt load during the recession periods also increased. Increasing ia by 20% resulted in a reduction in streamflow volume and increase in salt load. Increasing vertical conductivity of the top soil (K_{uv}) reduces the streamflow, increases salt load and vice versa. The lateral conductivity of the Groundwater Store (K_{ll}) has little effect on daily streamflow and has the greatest impact on daily salt balance. Two parameters related to salt release from Dry to Wet Stores and percolation (C_u, C) are significantly less sensitive compared to the lateral conductivity of the Groundwater Store (K_{ll}). Increasing the top soil depth (d) and the parameters related to its spatial distribution (b, c) results in a decrease in peakflow and increase in interflow and salinity.

The salt and water balance model presented in this paper was used as "building block" for developing a basin-scale operational catchment hydrology model. A large basin is divided into a number of response units to take into account the spatial distribution of rainfall, pan evaporation, soil salt storage and land use and the "building block" model was applied to each of the response units. Generated daily streamflow and salt loads from each of the response unit is routed downstream based on open channel hydraulics through a detailed channel and stream network. The basin-scale operational model has now been applied to predict the effects of logging, forest fire, clearing and reforestation on streamflow and salinity (Bari and Smettem, 2003; Bari and Berti, 2005). The spatial and temporal variations of land use were incorporated into the model by changing the response unit area where land use change took place. This model has also been successfully used for predicting the effects of different rainfall scenarios and climate change on catchment yield (Bari et al., 2005). Results demonstrate that the basin scale model can predict catchment processes using readily available data sets and requires minimum parameterisation and calibration.

8 Summary and conclusions

During the pretreatment period, daily streamflow was generated from saturated excess over land flow and interflow processes only for both catchments. The deep groundwater system did not play any role in flow generation, as it was about 15–20 m below stream surface. Average stream salinity was between 80 to 100 mg L^{-1} TDS. Following clearing of the Lemon catchment, there was an immediate increase in streamflow. Stream salinity increased to between 100 to 150 mg L^{-1} TDS. The groundwater system started to rise, dissolved the salt stored in the unsaturated zone and reached the stream invert in 1987. When the groundwater system reached the soil surface the stream became perennial and annual runoff volumes increased 4 to 5 times. Annual stream salinity increased to in excess of 2000 mg L^{-1} TDS and salt load increased 80 fold.

A coupled salt and water balance model was successfully developed and applied to represent the key hydrological processes associated with land use changes. The structure of the salt balance model remained practically identical to the water balance model. The coupled model has five stores: (i) Dry, Wet and Subsurface Stores, (ii) saturated Groundwater Store, and (iii) a transient Stream zone Store. The Dry and Wet Stores simulate the salt and water movement in the unsaturated zone and near-stream dynamic saturated areas. The Subsurface unsaturated Store represents the salt bulge and the salt fluxes due to percolation and recharge. The Groundwater Store quantifies the salt fluxes to the Stream zone Store. In the transient Stream zone Store a 'free mixing' between the inflow salt of surface runoff, interflow and baseflow components is considered.

The salt balance model was calibrated sequentially following successful application of the water balance model. We incorporated two parameters to represent diffusion-dilution-dispersion and salt fluxes due to preferential flow. The model has performed very well in simulating stream salinity generation processes observed at Ernies and Lemon catchments. The simulated and observed daily stream salinity and salt loads compared very well throughout the study period. Over all, the model predicted annual stream salt load by 7% and 6% higher than observed, with R^2 of 0.95 and 0.96 for Ernies and Lemon catchment, respectively.

Appendix A

Symbols and variable names

C	Parameter related to the salt release due to percolation (–)
C_d	Salinity of the Dry Store (mg L^{-1})
C_g	Salinity of the Groundwater Store (mg L^{-1})
C_i	Percolation salinity (mg L^{-1})
C_l	Salinity of the Subsurface Store (mg L^{-1})
C_{qr2}	Salinity of surface runoff Q_{r2} (mg L^{-1})
C_{qt}	Streamflow salinity (mg L^{-1})
C_r	Rainfall salinity (mg L^{-1})
C_{re}	Effective rainfall salinity (mg L^{-1})
C_{rf}	Salinity of the released water from Dry Store (mg L^{-1})
C_{rl}	Recharge salinity (mg L^{-1})
C_{sg}	Salinity of the Stream zone Store (mg L^{-1})
C_u	Parameter related to the salt release from Dry to Wet Store (–)
C_w	Salinity of the Wet Store (mg L^{-1})
d	Average depth of top soil (mm)
d_g	Average depth to groundwater level (mm)
d_l	Depth of the soil profile (mm)
d_s	Stream depth (mm)
Δd_g	Changes in groundwater level (mm)
I	Percolation (mm)
Q_i	Interflow) (mm)
Q_r	Total surface runoff (mm), ($Q_{r1}+Q_{r2}$)
Q_{r1}	Surface runoff (mm)
Q_{r2}	Surface runoff from “impervious area”(mm)
Q_b	Baseflow to stream (mm)
Q_{bl}	Baseflow to Stream zone Store (mm)
Q_{loss}	Groundwater loss below gauge (mm)
Q_t	Total streamflow (mm)
R	Actual rainfall (mm)
RE	Effective Rainfall (mm)
Rf	“Excess water” released from Dry Store to Wet Store (mm)
Rl	Recharge to Groundwater Store (mm)
S_d	Salt in the Dry Store (mg mm^{-2})
S_g	Salt in the Groundwater Store (mg mm^{-2})
ΔS_{sg}	Change in salt between Stream zone and Dry Stores (mg mm^{-2})
S_i	Salt transported by percolation (mg mm^{-2})
S_l	Salt in the Subsurface Store (mg mm^{-2})
ΔS_{gl}	Change in salt between Subsurface and Groundwater Stores (mg mm^{-2})
S_{qbl}	Baseflow salt to Stream zone Store (mg mm^{-2})
S_{qr1}	Salt load of surface runoff from pervious area (mg mm^{-2})
S_{qr2}	Salt load of surface runoff from “impervious area” (mg mm^{-2})
S_{qi}	Salt load of interflow (mg mm^{-2})
S_{qb}	Salt load of baseflow (mg mm^{-2})
S_{qlo}	Salt loss from Groundwater Store (mg mm^{-2})
S_r	Salt storage on the plant canopy (mg mm^{-2})
S_{re}	Salt fall on the ground with effective rainfall (mg mm^{-2})
S_{rf}	Salt transported by “excess water” from Dry to Wet Store (mg mm^{-2})
S_{rl}	Salt transported by recharge (mg mm^{-2})
S_{sg}	Salt in the Stream zone Store (mg mm^{-2})
S_{qt}	Total salt load to stream (mg mm^{-2})
S_w	Salt in the Wet Store (mg mm^{-2})
W_w	Water content of the Wet Store (mm)
W_d	Water content of the Dry Store (mm)
W_g	Water content of the Groundwater Store (mm)
W_l	Water content of the Subsurface Store (mm)
ΔW_{gl}	Changes in water between Subsurface and Groundwater Stores (mm)
W_{sg}	Water content of the Stream zone Store (mm)
ΔW_{sg}	Changes in water content of the Stream zone Store (mm)
θ_f	Average soil moisture content of top soil (mm^3 mm^{-3})

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