



Surface water as a cause of land degradation from dryland salinity

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Abstract. Secondary dryland salinity is a global land degradation issue. Because drylands are often less-developed, less-well instrumented and less-well understood, we often adapt and impose an understanding from different hydro-geomorphological settings. Dryland catchments are likely to exhibit some functional qualities of wet and hydrologically-connected landscapes, but also those more typical of flat and arid rangelands, smooth plainlands and deserts, where flow (dis)connectivity is an important feature. The functional hydrological mechanisms used to conceptualise causes of dryland salinity, originate from wet and more hydrologically-connected landscapes. They are then imposed with adjustments for rainfall and streamflow quantity to describe how hillslope-recharge processes interact with groundwater to cause dryland salinity. The pervasive understanding concludes that low flow yield from the end-of-catchment gauging stations indicates that land clearing alters water balance in favour of increased infiltration and rising groundwater that bring salts to the surface, causing land degradation from dryland salinity.

This paper presents data from an intra-catchment surface flow gauging network run for six years and a surface water-groundwater interaction site to assess the adequacy of our conceptual understanding of secondary dryland salinity in environments with low gradients and runoff yield. The aim is to (re)conceptualise pathways of water and salt redistribution in dryland landscapes, to investigate the role that surface water flows and connectivity plays in land degradation from salinity in low-gradient drylands. Based on the long-term end-of-catchment gauge, average annual runoff yield is only 0.14% of rainfall. The internal gauging network operated from 2007-2012 found pulses of internal water (also mobilising salt) in years when no flow was recorded at the catchment outlet. Data from a surface water-groundwater interaction site shows top-down recharge of surface water early in the water year, that transitions to a bottom-up system of discharge later in the water year. This connection provides a mechanism for the vertical diffusion of salts to the surface waters, followed by evapo-concentration and downstream export when depression storage thresholds are exceeded. Intervention in this landscape by constructing a broad-based channel to address these processes, resulted in a 25 % increase in flow volume and a 20 % reduction in salinity, by allowing the lower catchment to more effectively support bypassing of the storages in the lower landscape that would otherwise retain water and allow salt to accumulate.

Results from this study suggests catchment internal redistribution of relatively fresh runoff onto the valley floor is a major contributor to development of secondary dryland salinity. Seasonally inundated areas are subject to significant transmission losses and drive processes of vertical salt mobility. These surface flow and connectivity processes are not acting in isolation



to cause secondary salinity, but are also interact with groundwater systems responding to land clearing and processes recognised in the more conventional understanding of hillslope recharge and groundwater discharge. The study landscape appears to have three functional hydrological components: upland, hillslope “flow” landscapes that generate fresh runoff; 35 valley floor “fill” landscapes with high transmission losses and poor flow connectivity controlled by the micro-topography that promotes surface-groundwater connection and salt movement; and the downstream “flood” landscapes, where flows are recorded only when internal storages (fill landscapes) are exceeded. This work highlights the role of surface water processes as a contributor to land degradation by dryland salinity in low-gradient landscapes.

1 Introduction

40 Secondary dryland salinity is a severe land degradation problem, caused where land clearing alters the hydrological balance and rising saline groundwater degrades surface water resources and soils. Secondary dryland salinity (herein “salinity”) is a global issue reported in North America, central and southern Africa, Australia, South America, central and northern China, the Middle-East and central Asia (Ghassemi et al., 1995; Callow and Clifton, 2011). It is found in landscapes cleared for agriculture, where past marine conditions have left saline deposits or salts originating as an oceanic aerosol have accumulated 45 in the soils and the groundwater (Hingston and Gailitis, 1976; Ghassemi et al., 1995; Callow and Clifton, 2011). Over 30-40% of some landscapes can be affected (Ferdowsian et al., 1996), impacting infrastructure, agricultural production and biodiversity (Pannell, 2001; Cramer and Hobbs, 2002; Callow, 2012). Planning of adaptation and mitigation strategies to address the negative impacts of salinity requires a sound conceptual understanding, such that management interventions can address causal processes of salt redistribution and accumulation in the landscape.

50 Drylands occupy something of a mid-point along a hydrological spectrum between wet and hydrologically-connected landscapes, and dry poorly-connected landscapes. Hydrologically-connected temperate, sub-tropical and tropical catchments have higher and more reliable rainfall, are well-studied, better instrumented, and can support irrigated and seasonal rain-fed agriculture. At the other end are sparsely populated and poorly-instrumented flat and semi-arid “smooth plainlands”, rangelands and grading to desert areas, where rainfall is too low or unreliable to support seasonal agriculture. The paucity 55 of both hydrological data and detailed hydrological process studies in drylands, means that our conceptual understanding of dryland systems has often been transposed from the more intensively-studied and instrumented temperate and wet sub-tropical systems (Bracken and Croke, 2007; Bracken et al., 2013). This approach presumes the interplay of hydrological processes are functionally similar, such that surface and groundwater fluxes and water-balance partitioning can be inferred by scaling to the available precipitation and streamflow data. The concept of water balance still holds in drylands, with lower rainfall and runoff 60 and accounting for groundwater recharge, balanced by greater evapotranspiration potential (Tooth, 2000; Knighton and Nanson, 2001; Thornes, 2009; McMillan et al., 2011). Bracken et al. (2013) commented on the need for a better conceptual understanding of hydrological processes and connectivity that shape dryland catchments, to allow catchment managers to know where, when and how to manage adverse hydrological processes and landscape degradation. This is a particularly acute



65 problem in the World's dryland catchments impacted by salinity. The aim of this paper is to firstly review the past conceptual
basis for how land clearing impacts salinisation processes in dryland catchments, and then to present a dataset from a catchment
in Western Australia that highlights the complexity of surface water flows in shaping water and salt redistribution and export.
The findings from the dataset are used to reconceptualise the spatial and temporal variability in hydrologic pathways, which
can be used to inform improved land management practice.

2 Historical basis for conceptual models of dryland salinity

70 2.1 Dryland hydrological processes

Drylands are notable for a long history of land degradation challenges related to disturbance of hydrological balance, resulting
in issues such as desertification and salinity, with severe impacts on civilisations as far back as the Mesopotamian empire
(Conacher and Conacher, 1995; Conacher and Sala, 1998). The less predictable nature of rainfall and runoff, high levels of
socio-economic disadvantage and population growth, and hydrological data paucity, mean that drylands are under-developed
75 in terms of hydrological infrastructure, conceptual understanding and are sites of water vulnerability (Koochafkan and Stewart,
2008). Their predominantly mid-latitude location is notable as a region recognised as vulnerable to a future climate projected
to have declining surface and groundwater resources (Barron et al., 2012; McFarlane et al., 2012; Smettem et al., 2013;
Smettem and Callow, 2014). Attempts to identify a clear classification and understanding of dryland hydrology has been
discussed, with landscape properties and runoff regimes highlighted as potential key determinants of hydrology (McDonnell
80 and Woods, 2004; Wagener et al., 2007). Hydrological data scarcity, more limited process knowledge and variable
hydrological regime presents profound challenges to managing hydrological processes and land degradation including by
salinity in the World's drylands.

Drylands are influenced by processes such as antecedent conditions and seasonal rainfall accumulation that drive saturation-
excess from a partial-contributing variable source area, similar to wetter and more temperate and tropical areas (Ruprecht and
85 Schofield, 1989; Ruprecht and Stoneman, 1993). They are also influenced by infiltration-excess (Hortonian) processes, event
and episodic flow regimes and limited hydrological connectivity with high transmission losses, typical of drier, semi-arid
landscapes (Walker et al., 1995; Tooth, 2000; Nanson et al., 2002; Bracken and Croke, 2007; Koochafkan and Stewart, 2008;
Powell, 2009; Bracken et al., 2013). Work on improving hydrological understanding and prediction in data-scarce basins has
emphasised the importance of understanding threshold behaviour including activation and deactivation of dynamic (surface
90 and subsurface) drainage networks and landscape specific emergent behaviours that can override small-scale processes
(Hrachowitz et al., 2013).

Themes that emerge from the limited research on hydrological processes in the World's drylands highlight the significant role
of processes related to water connectivity, including lateral and longitudinal hydrological redistribution of surface water and
surface-groundwater interactions, including in work from northeastern Brazil (Costa et al., 2012), Africa (Bauer et al., 2006;
95 Bonell and Williams, 2009) and Spain (Nicolau et al., 1996; Ceballos and Schnabel, 1998; Abrisqueta et al., 2007).



Ecohydrology and interaction of vegetation with rainfall, topography, aquifers and runoff is also highlighted as significant (Gifford, 1978; Ludwig et al., 1997; Ludwig and Tongway, 2000; Ludwig et al., 2005; Wilcox and Newman, 2005; Eamus et al., 2006; Callow, 2011; Turnbull et al., 2012; Wang et al., 2012). Topographic subtleties are disproportionately important in low-gradient drylands as microtopography from the Earth surface, but also organic processes such as animal workings, woody
100 debris, rocks and litter debris dams can have a significant influence on hydrological and biogeochemical pathways (Ludwig et al., 2005; Wilcox and Newman, 2005). Micro-scale processes and vegetation-hydrology-topography interactions are also recognised as particularly significant (HilleRisLambers et al., 2001; Ludwig et al., 2005; Dunkerley, 2011; McGrath et al., 2012). The trigger–transfer–reserve–pulse (TTRP) framework of Ludwig et al. (1997) and Ludwig and Tongway (2000) emphasises the role of microtopography in the form of litter dams (Ludwig et al., 2005), that controls patterns of water
105 redistribution and longitudinal connectivity due to high depression storage of “run-on” water. Bartley et al (2008) demonstrated the interaction of hydrological, geomorphological and ecological processes across multiple scales controls runoff and erosion in the semi-arid rangelands.

2.2 Hydrological processes causing dryland salinity

Native vegetation systems of the World’s drylands have been extensively clearing for agricultural development. Deep-rooted
110 vegetation has been replaced with seasonal cropping and pasture and shifted hydrology towards increased runoff and groundwater recharge (Ruprecht and Schofield, 1991; Commander et al., 2001; Muirden et al., 2003; Callow and Smettem, 2007). In the study region, annual and peak flood discharge increased by a factor of 2-4 times (Pen, 1999; Bowman and Ruprecht, 2000; Muirden et al., 2003; Callow and Smettem, 2007), groundwater recharge increased by 5-30 times (0.02 – 0.14
115 mm yr⁻¹ under native woodland systems to 6 – 30 mm yr⁻¹ with agriculture) (George, 1992; George and Conacher, 1993), and groundwater levels risen by up to tens of meters (George and Conacher, 1993; Callow and Smettem, 2007; Bennett and George, 2008) expanding the saturated, shallow groundwater areas and other partial-source areas (Ruprecht and Schofield, 1989, 1991; Ruprecht and Stoneman, 1993). Responses of water resources and biodiversity to the resultant increase in landscape salinisation have been reported for over a century (Mann, 1907; Wood, 1924; Wood and Wilshire, 1928; Bennett and Macpherson, 2002; Halse et al., 2003; Nielsen et al., 2003; Peck and Hatton, 2003; Callow and Smettem, 2007).

120 2.2.1 Hillslope-recharge model

The association of salinity and land clearing was recognised from the first decade of the twentieth century, associated with impacts on water resources used for railway locomotives (Mann, 1907). Wood (1924) reported that “*where destruction of the native vegetation has taken place rapidly, there has followed a very noticeable increase in salinity in the streams draining that area*” (Wood, 1924, p. 35). Wood (1924) proposed that land clearing increases the volume of water on the hillside that will
125 then raise the water-table near the watercourse, where this is sufficiently pervious the water will rise through it bringing salts to the surface and as the area dries leaves salinity on the surface as a salty incrustation. (see Wood, 1924, p. 40-41 for full description)



The hillslope-recharge model of Wood (1924) has been supported by subsequent work on the causes of salinity, and in designing and evaluating management interventions targeted at mitigating and adapting to land degradation caused by salinity
130 (Hatton and Salama, 1999; Hatton and Nulsen, 1999; Hatton et al., 2003). Conacher (2001; 2001) and George and Conacher
(1993) identified four mechanisms for development of salinity: 1) increased overland flow and surface runoff; 2) increased
regional groundwater throughflow and the development of perched aquifers; 3) increased infiltration to deep aquifers leading
to rising water-tables; and 4) increased soil throughflow and infiltration to deep groundwater, leading to a mixing of perched
and deeper aquifer systems in saline seeps. George and Conacher (1993) and George et al. (2008) found that event recharge is
135 significant and large rainfall events can account for large proportions of annual recharge and lateral expansion of the salinised
area. Similar to Wood, George and Conacher (1993) proposed that mechanism three was the dominant causal process leading
to secondary salinity in dryland areas.

Managing salinity has focused on what Hatton and Nulsen (1999) termed functional ecosystem mimicry, where perennial
vegetation was re-introduced into the landscape. Evaluation of this effort found that in areas of higher rainfall and on sandplain
140 seep sites, recharge management has delivered direct impacts in reducing groundwater levels and the expansion of areas
affected by secondary salinity (Bell et al., 1990; George et al., 1999; Bennett and George, 2008). Results from low-gradient
areas with valley-floor salinity and in lower rainfall zones (<600mm yr⁻¹) display no evidence of positive impacts (George et
al., 1999; Johnsen et al., 2008). This raises the question as to whether the extent of intervention (revegetation) is not sufficient
(Hatton and Nulsen, 1999), or whether there is an important process-response difference between the higher gradient and
145 rainfall areas that are more hydrologically-connected, and the drier and lower-gradient landscapes. There is the potential that
adapting the understanding from one landscape type (wetter and connected) to another (drier, flatter and disconnected), has
not been able to capture the full subtlety of processes causing land degradation by salinity in the drier and flatter setting.

2.2.2 Surface water redistribution and dryland salinity

Less extensively reported in published work on causes of salinity is work that highlights the potential role of surface runoff.
150 Teakle and Burvill (1938) reported that in addition to the processes captured by Wood's (1924) hillslope-recharge model,
dryland salinity can develop due to two additional factors. A seasonally perching aquifer (saturated source area) was observed
to form where regional groundwater throughflow emerged at the break of slope or due to sub-surface structural features (such
as dykes and silicified fault plains). This results in saline waterlogging or a hillslope saline-seep, developing as a seasonal
feature this is common in sandy surface soils over clay and for deeper sand soils termed by George (1990) as "sandplain seeps".
155 The second mechanism reported by Teakle and Burvill (1938) was related to observations of surface expressions of salinity
were that the watertable was not directly connected to the soil surface. Teakle and Burvill (1938) suggested that these
developed in poorly flushed soils where salts can move salts vertically through the unsaturated zone by diffusion in soil
moisture and evapo-concentration at the surface. They reported that salinity developed where the saline watertable was between
4 ft (1.2 m) to 10 ft (3.0 m) below ground level (BGL) at the end of winter, but most common where the saline water table was



160 less than 5 ft (1.5 m) BGL, and in cracking and swelling clays depressions “*where the micro-relief favours surface evaporation*” (Teakle and Burvill, 1938, p.243).

Nulsen (1981) found that a saline groundwater depth of 1.8m BGL was a critical limit on wheat crop growth in the drier and flatter landscapes, well below the rooting zone of this annual species. Nulsen and Henschke (1981) reported the lateral redistribution of runoff from hillslopes to the valley floor where there was groundwater recharge through preferred-pathway
165 flow on the valley floor. In a different setting, Jones (2000a, b) questioned the recharge efficiency of grasslands and the role of taproots as a vertical pathway for groundwater rise to cause salinity in a low hydraulic conductivity sub-soil (as proposed by the hillslope-recharge model). They suggested that surface flows may be important in causing salinity in low-gradient landscapes. Bann and Field (2006b, a) used the term “surface-water salinity” in south-eastern Australia to describe similar processes of surface water redistribution and valley-floor vertical recharge causing salinity. Other work describe how
170 waterlogging caused by build up of water behind topographic obstacles, such as roadways/railways with poor culvert capacity as a cause of salinity (Cattlin et al., 2002; Cattlin and Farmer, 2004; Cattlin, 2006).

2.2.3 A role for surface water redistribution causing salinity

In summary, the pervasive conceptual understanding of salinity is based on the hillslope research model of Wood (1924), and subsequent work by George and Conacher (1993) and others. Causal process can be summarised as land clearing altering
175 hydrology in favour of higher hillslope recharge that causes rising salinity groundwater that degrades soil and water resources in low-lying landscapes. This understanding may have some limitations in adequately resolving dynamics of water and salt flux and pathways of salt accumulation within the unsaturated root zone., especially given lateral groundwater flow rates are so low (McFarlane et al., 1989). The potential role of surface water runoff and redistribution is not well understood in dryland, saline environments and the role that this may have as a contributor to salinisation.

180 In this paper we investigate surface streamflow and surface to groundwater connectivity data from a high-resolution gauging network within a dryland catchment to determine whether there is evidence to suggest a role for surface water processes as a contributor to secondary dryland salinity. The initial focus is the long-term, end-of-catchment gauging data and is evaluated with respect to the prevailing understanding of hydrological partitioning of fluxes through the hillslope-recharge model, as applied to a hydrologically-connected landscape. Data on water and salt yield from a high resolution internal catchment
185 gauging network (above the long-term gauge) that was operated for six years is used to investigate surface water runoff and patterns of catchment internal water redistribution and connectivity, and salt flux and yield from the landscape. Data from a surface water-groundwater (SW-GW) interaction site on a valley-floor area with micro-topography and surface water inundation is then evaluated in relation to water fluxes and implications for salinity processes. Finally, data on water transmission and salt yield from a management intervention where a broad-based channel was constructed to remove micro-
190 topography, reduce inundation and increase connectivity in a valley-floor location is evaluated in relation to the role of surface water in dryland salinity and effectiveness of this intervention.



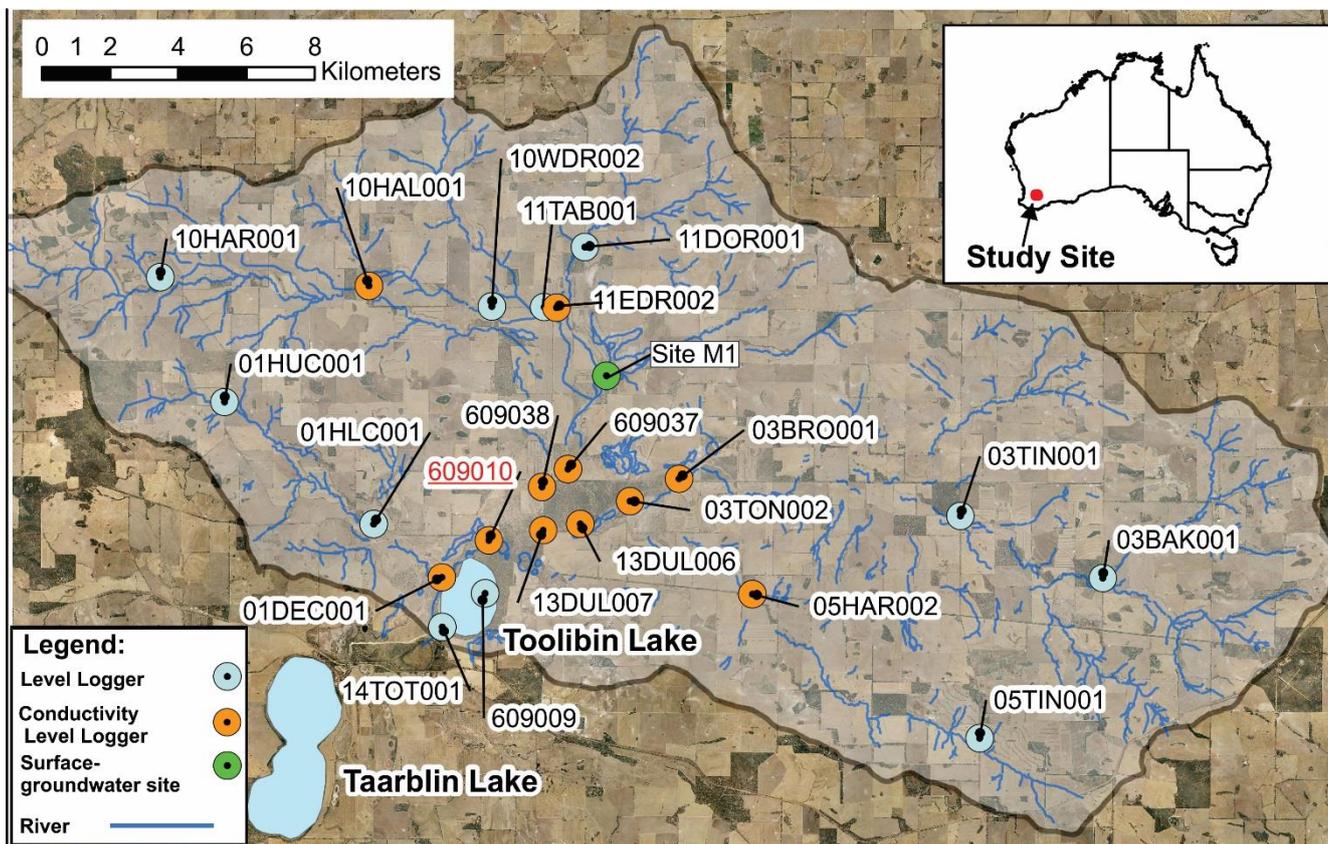
3 Experimental site and data collection

3.1 Study site

195 Toolibin Lake is an ephemeral wetland catchment (485 km²), within the broader Blackwood River catchment located in the
Wheatbelt Region of Western Australia (Fig. 1). The catchment sits atop the Yilgarn Craton, an Archean Craton-aged deposit
of primarily granitoids. Deep weathering of these granitoids and laterisation occurred under a previous wetter and more humid
climate (Mulcahy, 1967; Johnstone et al., 1973), leading to the characteristic duplex (texture contrast) lateritic soils typical of
the region (Commander et al., 2001; Verboom, 2003). Due to the age and stability of the landscape, salts derived from oceanic
aerosols have accumulated in the soils and groundwater of this region (Hingston and Gailitis, 1976), and relict palaeodrainage
200 features affect contemporary movement of the (typically saline) groundwater and influence surficial hydrological processes
(van de Graaff et al., 1977; McFarlane et al., 1989; Clarke, 1994; Beard, 2003). The Toolibin Lake catchment is 140km east
of the Darling Range atop the Yilgarn Plateau, with gently sloping hillslope and predominantly wide and flat valley floor
landforms that have significant local micro topography and overlie palaeochannel valley-fill sediments (Commander et al.,
2001; Beard, 2003).

205 The region has a Mediterranean-type climate, experiencing cool and wet winters, with hot and dry summers. Winter rainfall
results from cold fronts embedded in westerly moving low pressure cells passing over the region (Sturman and Tapper, 1996).
Floods are associated with both ex-tropical cyclonic lows that can track across the region during the months of November to
April, and cold fronts that bring widespread (though lower intensity) rainfall during winter and spring months, typically on a
wet catchment. Average annual rainfall (from 1975-2009) in the Toolibin Lake catchment grades west to east from 390 mm
210 to 350 mm (Callow et al., 2008). There is high annual rainfall variability, and a marked decreasing trend since the mid-1970s
for stations in this catchment (Callow et al., 2008), consistent with what is reported for southwestern Australia (Smith et al.,
2000; Indian Ocean Climate Initiative, 2002; Callow and Smettem, 2007). Stations now receive an average of 40 mm to 80
mm per year less than the pre 1975 average in this catchment (Callow et al., 2008). Hence, rainfall data is analysed within this
paper with reference to the post-1975 period, rather than the entire record (except where otherwise stated).

215 The landscape was originally dominated by diverse Eucalypt woodlands and heathlands. Minor clearing began in the late
nineteenth century, concentrated on clay rich areas in valleys, with the upper Toolibin Lake catchment areas cleared mostly
after World War II, continuing until the 1970s as agriculture became increasingly mechanised (Watson, 1978). Only around
10 % of the native vegetation remains, and current land use is dominated by annual cereal cropping and pasture grazing by
sheep, often in mixed cropping-livestock systems (Callow et al., 2008; Muirden and Coleman, 2014).



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Figure 1: Toolibin Lake catchment showing the monitoring sites coded according to whether conductivity and/or level data recorded. Drainage lines highlight the often discontinuous and meandering surface hydrologic pathways with poor downstream connectivity in valley floor. Map created with field data and open-access data through the Western Australia Government Shared Location Information Platform and creative commons data from Geoscience Australia.

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A long-term, streamflow gauging station is operated by the Department of Water and Environmental Regulation (DWER) just above Toolibin Lake (Station Number: 609010, Fig. 1). Rainfall data was obtained from long-term Australian Bureau of Meteorology rainfall stations at Wickepin (10654, opened 1912) and Avoca (10671, opened 1930) as they contain the longest continuous record and are located to the north-west and south-east of the catchment. A high resolution surface water gauging network was installed and operated from 2007-2012 to measure internal catchment hydrological yield and patterns of connectivity, salt yield and redistribution (Fig. 1).

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A combination of capacitance probe loggers (Scott Parsons Electronics (SPE) USB Capacitance Loggers), InSitu AquaTroll 200 integrated level (pressure) and conductivity probes, and Unidata 6536D conductivity loggers, were installed to monitor streamflow, salinity and groundwater levels. Sites were serviced three monthly, with loggers downloaded and sensor calibration of capacitance probes in “dirty” and then “clean” conditions used to create a phased linear change calibration managed in a Hydstra hydrological database. Due to the salinity of streamflow (that can exceed the salinity of seawater), laboratory testing of capacitance loggers was undertaken to determine their overall accuracy and susceptibility to calibration

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drift under higher salinity water (Callow et al., 2008). Accuracy was better than ± 10 mm at full scale under all conditions, with a mean error of 3mm (2m is full scale, i.e. $<0.5\%$ error) for all calibration tests across water that varied in salinity from tap-water (~ 400 mgl⁻¹) to water approximating seawater (33,000 mgl⁻¹) (Callow et al., 2008). Sites recording conductivity were used to calculate salinity and salt load by converting conductivity to salinity (or Total Dissolved Salts (TDS) (Callow et al., 2008). Salt and water flux is reported based on a water year, starting from 1st April each year.

Gauging sites were surveyed using either a Topcon total station or a Magellan ProMark3 Real-Time Kinematic Differential Global Positioning System (RTK-DGPS) (depending on the tree canopy density). A Valeport 801 single axis electromagnetic velocity meter was used to gauge streamflow greater than 7 cm deep that occurred during gauged events in 2007, 2008 and 2012. Point survey, gauging and LiDAR data (where available) was also used to calculate stage-discharge rating curves using 1-D HECRAS (U.S. Army Corps of Engineers, 2008), with stage and salinity data plus rating curves managed within the Hydstra program used to calculate total discharge and salt loads. Details on data review and quality control are described in detail by Muirden and Coleman (2014).

A surface water-groundwater interaction (SW-GW) monitoring site was established at Site M1 (Fig. 1) in April 2008. RTK-DGPS was used to collect over 7,000 spot heights through a 0.28 ha valley floor site, with points of vertical accuracy lower than 3 cm excluded, to create a valley-floor 0.5 meter Digital Elevation Model (DEM). Site M1 was located in a DEM mapped surface water inundation area. Upstream and downstream surface water loggers were also installed to monitor surface inflow and outflow, with DAFWA pluviometer rain gauge (“Martins”) located 2 km from this site. A 4.5 inch (114 mm) hollow-stem auger was used to drill to a depth where the pallid zone (chemically-weathered kaolinitic sapriolite) was reached, with 3 inch (76mm) plastic inserts used to collect core samples. Fully-slotted PVC pipe (80 mm Class 12 Pressure pipe) was inserted as an observation bore. Solid stem augers (3.5 inch) were then used to target drilling into three identified permeable layers, to install: deep (drilled to 6.2 m, slotted from 5-5.5 m); intermediate (drilled to 4.5 m, slotted from 3.6-4.0 m), and; shallow (drilled to 2.5 m, slotted from 1.4-2.0 m) piezometers. Piezometers were 50 mm Class 12 PVC solid pressure pipe with slotted section in target layers, sealed above and below the target layer with bentonite (pellets). Loggers were installed in groundwater monitoring infrastructure (15 minute logging) and the surface water sites (five minute logging), calibrated to protocols outlined. Vertical hydraulic gradient was used to indicate up or down water flux direction, calculated for the shallow to intermediate and intermediate to deep piezometers, determined as the overall difference of the water levels divided by the mean depth difference of the slotted section.

3.2 Valley-floor channel construction

During 2009, a new waterway was constructed to connected stations 609037, 609038, 03TON002 and 05HAR002 concentrating flow directly into Dulbinning Lake (Fig. 1 for locations). The waterway was located based on LiDAR and high-resolution topographic surveying to identify low-points and to connect them, preventing transmission loss and internal storage. The waterway was designed and constructed as a low-gradient, broad-based channel, approximately 25 m wide, 0.4 m deep and running at the valley floor gradient ($\sim 0.0003 - 0.0015$ m m⁻¹) and designed to carry a 1:3 yr flow (Fig. 2). The waterway



270 was constructed with the spoil removed to allow lateral inflows from adjacent areas of the reserve and to ensure that spoil
dump levees (as is the norm for the construction of such channels) did not exacerbate waterlogging on areas lateral to the
constructed channel and hydrologically disconnect the channel from the wetland and prevent lateral inflows. The design
allowed for larger flows to spread and dissipate across the valley floor, but then drain back into the channel on the falling limb
of the flow pulse.



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Figure 2: New broad-based channel implemented in Dulbinning Nature Reserve. Channel dimensions at this location are 23m wide, 0.55m deep. Water depth in this image is 0.18m.

4 Results

280 4.1 Hydrological yield at catchment outlet

The long-term gauging station collects data between Dulbinning Lake and the inflow to Toolibin Lake (DWER Station 609010, Fig. 1). Analysis of the long term gauging record for Toolibin Lake inflows (Station 609010) from September 1978 to December 2012, reveals that flow is only recorded on 4% of days, with there was only flow during 13 % of months, with 40 % of years recording no flow days across the entire water year. The 1:5 yr and 1:10 ARI peak streamflow is $2 \text{ m}^3\text{sec}^{-1}$ and $10 \text{ m}^3\text{sec}^{-1}$, respectively, from a catchment with an area of 485 km^2 with an average rainfall of around 360 mm.

The infrequent inflow events to Toolibin Lake tend to occur at two times; either the end of winter and early spring in wetter years, or in summer due to ex-tropical cyclone activity. Winter streamflow is only typically experienced during June to September, with mean monthly discharges of 140, 394, 184, 105 ML respectively. January has an anomalously high mean monthly discharge relative to non-winter/spring months (142 ML), skewed by one event, the highest on record which occur during the summer 1982 floods associated with ex-tropical cyclone Bruno. Average streamflow by rainfall decile, summer events show a significant threshold jump for streamflow between Decile 7 (30 ML) and Decile 8 (366 ML) years, but for late

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winter and early spring events, this occurs between Decile 5 (153 ML) and 6 (915 ML). Mean average annual discharge at the long-term gauge is 170.6 ML yr^{-1} (Muirden and Coleman, 2014), which equates to a mean annual runoff yield of streamflow of 0.14 % of rainfall.

295 4.2 Internal runoff generation, water redistribution and hydrological connectivity

4.2.1 Water yield

The high resolution gauging network is depicted schematically in Figure 3, and presents results for annual flow of water (black) and salt (red, for sites with those data) within the Toolibin Lake catchment. The streamflow data highlights that flows frequently occur upstream of the long-term gauge, and annual yield and flow is higher at some of these locations than at the downstream location. During the dry years of 2007 (i.e. water year starting 1st April 2007 in including the winter (wet season) of 2007), 2010 and low-flow year of 2011 (at the end-of-catchment gauge, 609010), there are significant flows and water redistribution with the catchment that do not connect through to the long-term gauging site.

Based on post-1975 rainfall data, the study period included: an average year (2007 - Decile 4), two wetter years (2008 - Decile 8 and 2011 - Decile 9) and three extreme dry years (2009 - Decile 1, and 2010 and 2012 which respectively represented the driest and second driest years since 1975). Flow yield at the long-term gauge, recorded zero flow in the Decile 4 year (2007) and flow in Decile 8 (2008) rainfall year are consistent with the activation thresholds discussed above for this site based on the analysis of the full streamflow record (since 1978). Data from the high-resolution gauging network shows that in 2007 there was significant streamflow within the catchment but this did not connect to the long-term gauging station. Internal catchment surface water redistribution also occurred in the other no outflow year (2010, which was the second driest year on record), with up to 66ML of discharge measured at internal catchment gauges.

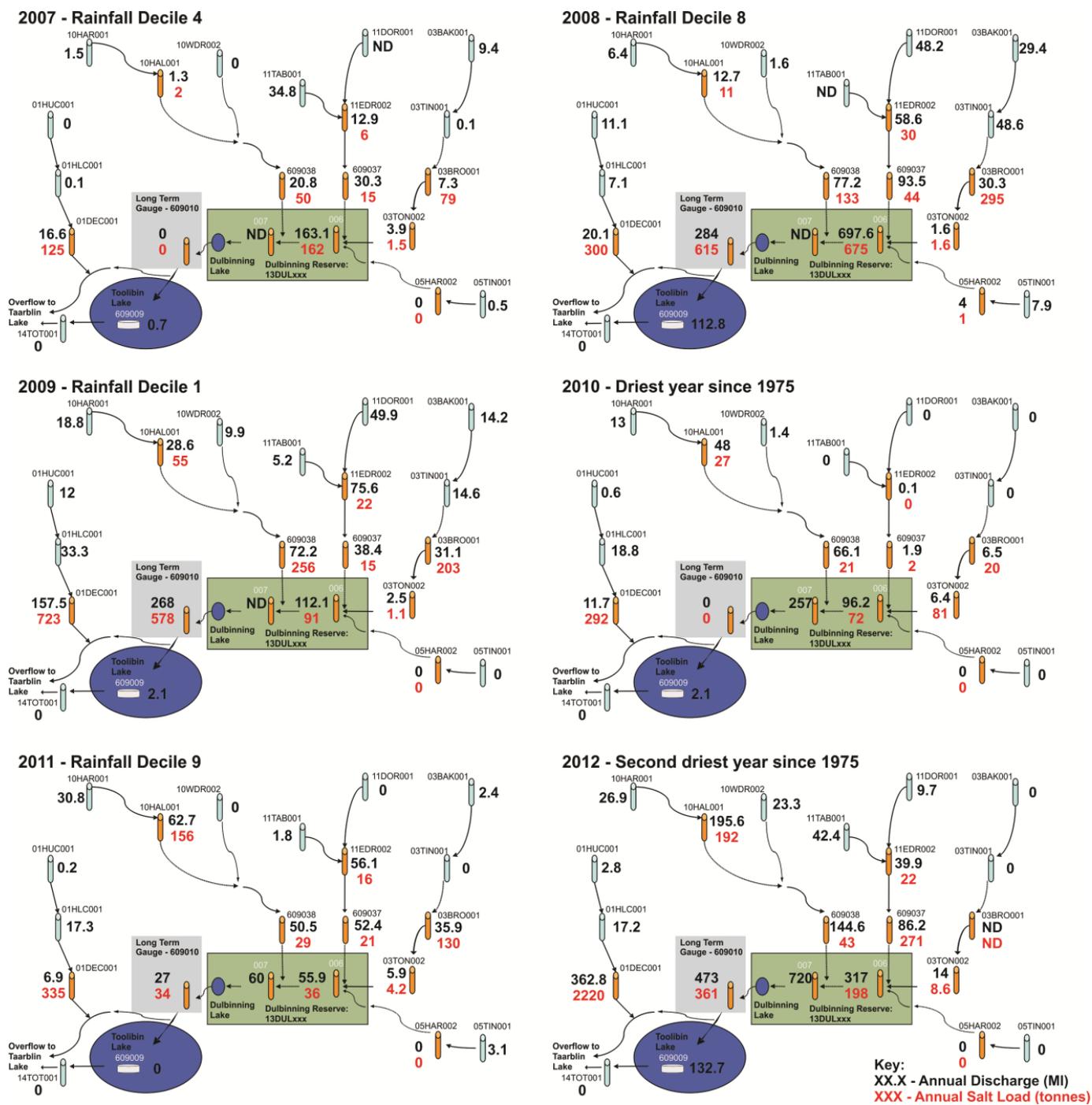
Due to the management intervention to increase hydrological connectivity, results for streamflow after 2009 in locations downstream of the Dulbinning Nature Reserve (including the long-term gauge) need to be considered in the context of the surface water engineering interventions that have changed catchment behaviour (see section 4.4). Streamflow at the long-term gauge was recorded during the wet years of 2008 (Decile 8) and 2011 (Decile 9), but also the dry years of 2009 (Decile 1, with large rainfall event) and 2012 (Decile 1 and second driest on record, flow from a late summer event) that post-dated this management intervention.

4.2.2 Salt yield

Opportunistic sampling of water quality during a flow event in July 2007 found that the gauging sites in the east of the catchment had salinity values comparable to rainwater on hillslopes, measured at $\sim 100 \text{ mg L}^{-1}$ during rainfall events with short-lived runoff. Logger data for the same event reported values of $2,150 \text{ mg L}^{-1}$ at 13DUL006 within Dulbinning Nature Reserve, and sites 609037 and 609038 had salt concentrations peaking at $4,000$ to $13,600 \text{ mg L}^{-1}$.



Salt loads calculated at the ten stations measuring conductivity and flow through the network presents a complex pattern of salt flux and export. In 2007, there was significant net input of salt from the surrounding landscape to the valley floor (i.e. Dulbinning Nature Reserve), which is not transferred through to Toolibin Lake (no flow recorded the long-term gauge, 325 609010). A salt load of 66.5t was measured entering the reserve (609037: 15 t; 609038: 50 t and 03TON: 1.5 t) which increased to 162 t at 13DUL006 in the middle of the Dulbinning Nature Reserve. There was no streamflow at the entry to Toolibin Lake (609010), so no export of the salt from Dulbinning Nature Reserve and Dulbinning Lake in that year. In 2008 (a wet Decile 8 rainfall year), there were numerous streamflow events connecting through the landscape during winter. Data suggest that during this wetter year, there was an initial flushing of surface stores of salt followed by a sequence of flow events that allowed 330 for limited input of salts from the surrounding landscape onto the valley floor. In some years (2009, 2012), there appears a larger export of salts through the long-term gauge into Toolibin Lake (609010), than enters Dulbinning Nature Reserve in that single year.



335 **Figure 3:** Annual discharge data (MI) (black data) and salt load (tonnes per year in red) for the different gauging stations across the study period (2007 – 2010). Note that ND is no data due to equipment failure.



4.3 Surface water - groundwater connectivity and vertical recharge processes

A surface water-groundwater (SW-GW) interaction site was established to measure the direction of vertical water movement in a valley-floor landscape. Data from the SW-GW interaction site across a water year, identifies three broad characteristic stages (Fig. 4). At the end of summer, the valley-floor areas are dry and characterised by large surface cracks, up to 3 cm wide and 50 cm long and greater than 30 cm deep. The first stage (Stage 1) is dominated by surface flows that drive top-down recharge but has two sub-stages (1a, 1b) within it. Initially, infiltration relative to rainfall is rapid and responsive (Stage 1a, Fig. 4), where macropores likely facilitate rapid infiltration of direct rainfall and surface flows (run-on) that has a rapid preferential pathway flow and allows rapid top-down early-season recharge. As the water year progresses, the system transitions to a state still dominated by surface inundation and top-down recharge, but where the hydrological response and recharge rates relative to rainfall is more subtle (Stage 1b). As soils saturate and macropores close, matrix flow becomes the dominant flux mechanism and the seasonal surficial aquifer becomes connected. The system behaves as a semi-confined aquifer similar to Drake et al. (2013), though the vertical hydraulic gradient still remains downwards through to mid to late winter.

As the aquifer connects, there is evidence for a transition to the bottom-up groundwater discharge in later winter and early spring months (Stage 2). At this stage the hydrological behaviour is as expected under the hillslope-recharge model, whereby hillslope recharge and lateral movement of groundwater to the valley floors drives a negative hydraulic gradient pushing shallow groundwater vertically, a bottom-up groundwater response. Groundwater potentials reach or exceed the ground surface, and fresher surface water flows created the potential for the vertical diffusion of salts via matrix flow due to the concentration gradient from saline soil to fresher inundation. Where surface inundation ponds salts are subject to evapo-concentration and ultimately retained in the surface soils or as a surface salt crust, or when inflows exceeded depression storage thresholds, salt may be exported horizontally and down system.

From late spring, the system dries and groundwater levels fall and then de-couples from the surface (Stage 3). Soils desiccate and macropores re-develop as the system is reset for the subsequent water year, or in the case of March 2010, a dry-season thunderstorm (Fig. 4), with a similar top-down and highly responsive behaviour to rainfall (Stage 1a).



Martins Surface Water Groundwater Interaction Site 1 - ASWTLBSGWM501

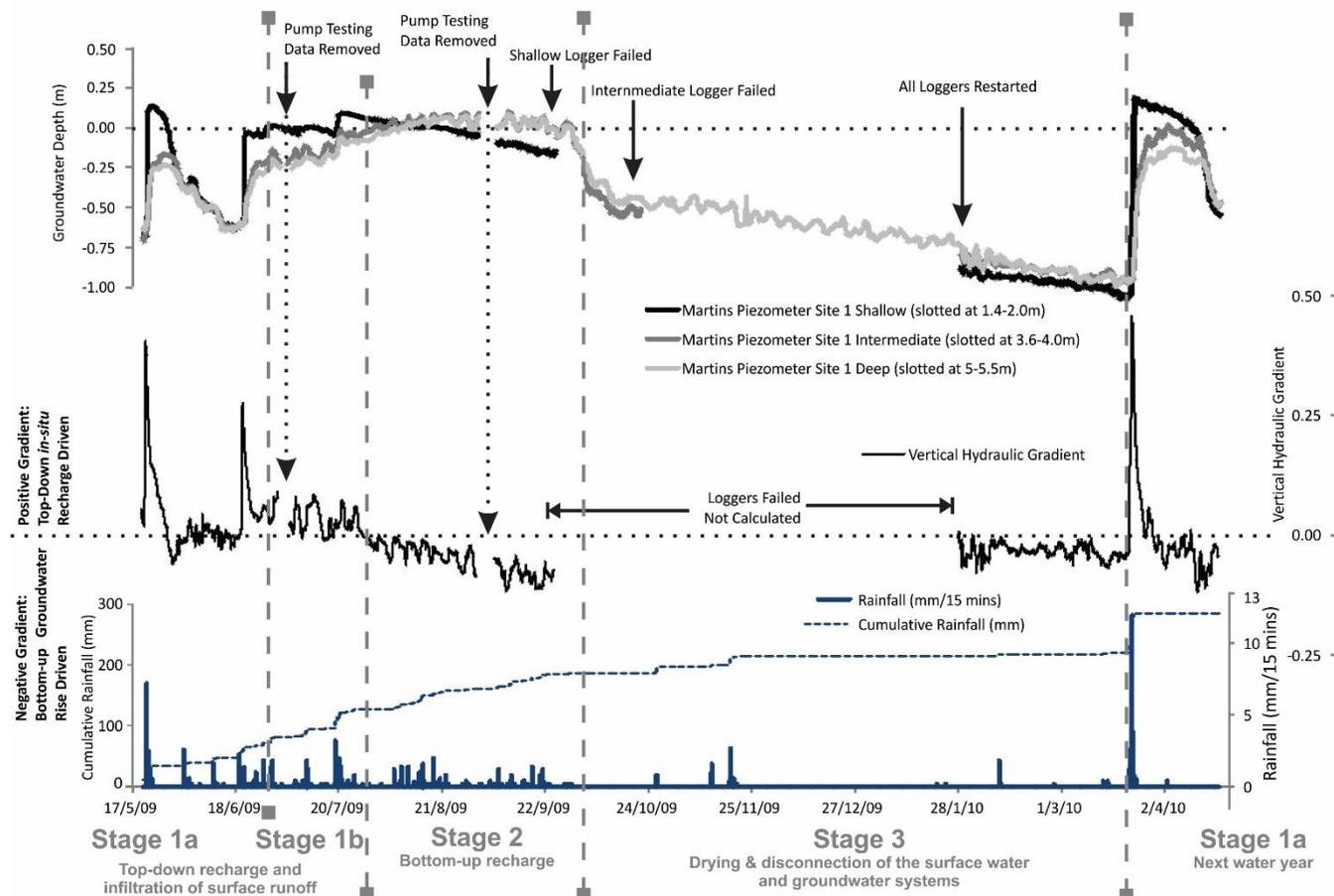


Figure 4: Groundwater data for Martins Site M1, showing movement of the shallow, intermediate and deep piezometers and the overall vertical hydraulic gradient from May 2009 to June 2010 and three stages of SW-GW interaction.

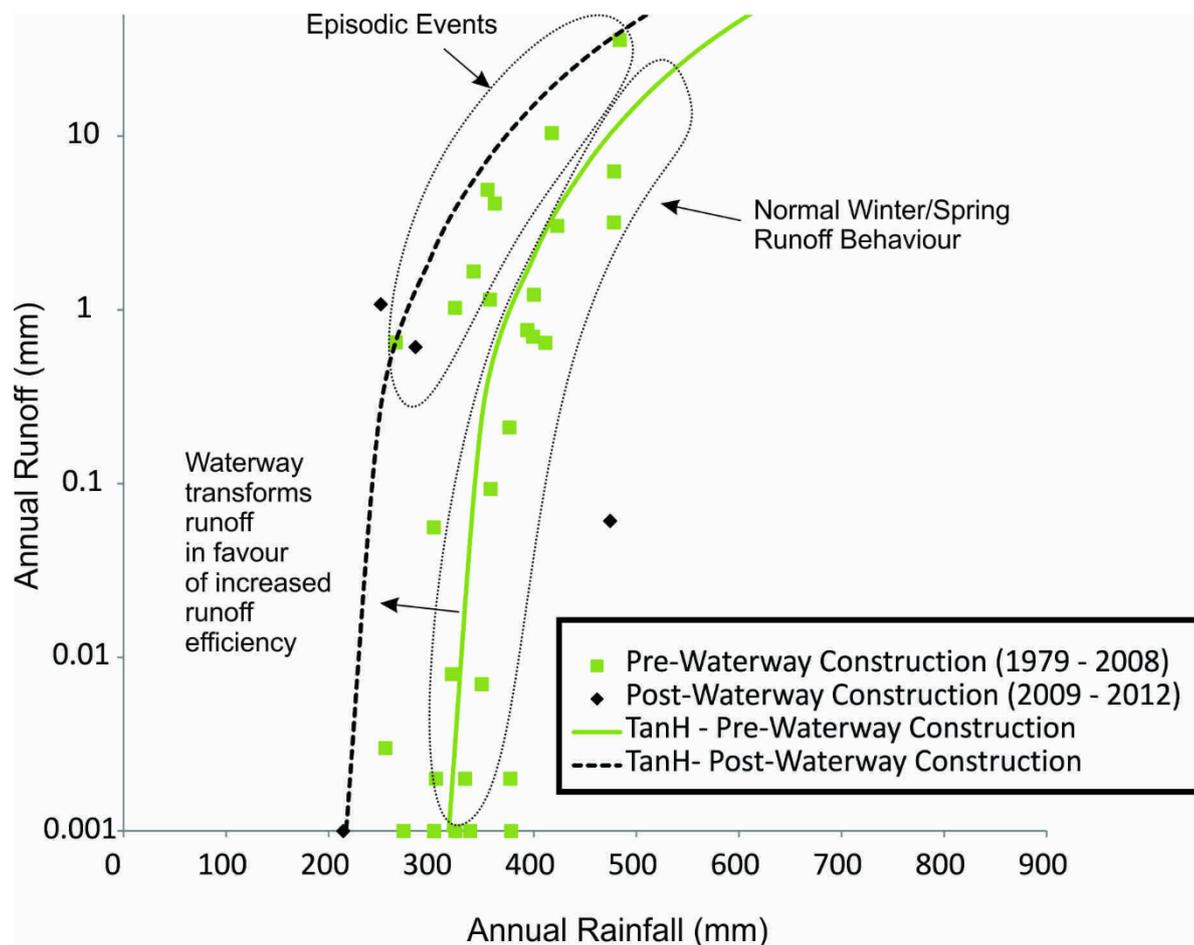
4.4 Manipulating surface water connectivity

365 The new channel constructed in the Dulbinning Nature Reserve aimed to increase connectivity of otherwise ponded areas in the valley floor, to enhance the overall water yield and reduce salt export to Toolibin Lake. The hypothesis was that by minimising ponding, the time for exchange and accumulation of salts from groundwater into the surface water would be reduced and thereby reducing the load exported downstream. Following construction in early 2009, the hydrological behaviour of the catchment, as represented by the end-of-catchment gauge (609010), can be seen to change markedly (Fig. 5). This demonstrates a considerably higher yield as water is more efficiently transmitted from landscape positions receiving run-on from further upstream areas (similar to location M1, presented in section 3.3), and less impacted by micro-topography in the valley floor. This occurred in all years post-construction (2009, 2010 and 2012), aside from 2011. This anomalous result is most likely a response to the re-wetting of the catchment and high total, but low-intensity, rainfall that was experienced after the driest year on record (2010); the combination of numerous low intensity events and dry antecedent conditions considerably

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375 reduced the runoff efficiency. This confirms the challenge of ascertaining hydrological behaviour from the gauge lower in the landscape, and the high non-linearity occurring in these landscapes with weak gradients, and highly episodic rainfall. Analysis of salt load transmitted in the limited number of events post-construction found that the salinity of streamflow reaching Toolibin Lake was 20% lower when compared to similar magnitude events before construction.



380 **Figure 5: The annual rainfall-runoff data shows the role that microtopography plays within low-gradient drylands, with a pronounced change in runoff efficiency recorded at the long-term gauge after the construction of the waterway through Dulbinning Nature Reserve in 2009.**

5 Discussion

385 The results from the long-term, end-of-catchment gauge are consistent with the interpretation of functional catchment hydrology and pervasive model of dryland salinity. That is, low runoff and inferred high hillslope recharge that drives groundwater rise. However, the data from a high-resolution internal surface gauging network, combined with the results from a valley floor SW-GW interaction site, and the management intervention to improve hydrological connectivity, all suggest an important role for surface water processes in the redistribution of salt and the ultimate manifestation of dryland salinity within



low-gradient dryland landscapes. In particular, variability and threshold behaviour in surface water processes that lead to water
390 run-on and valley-floor inundation are important in shaping dryland salinity in low-gradient valley-floor locations where
microtopography creates the potential for surface ponding and vertical salt movement via diffusion. The insights from this data
set allow us to refine and add to the conceptual model for the hydrologic drivers of dryland salinity.

5.1 A water balance approach to the hillslope-recharge model

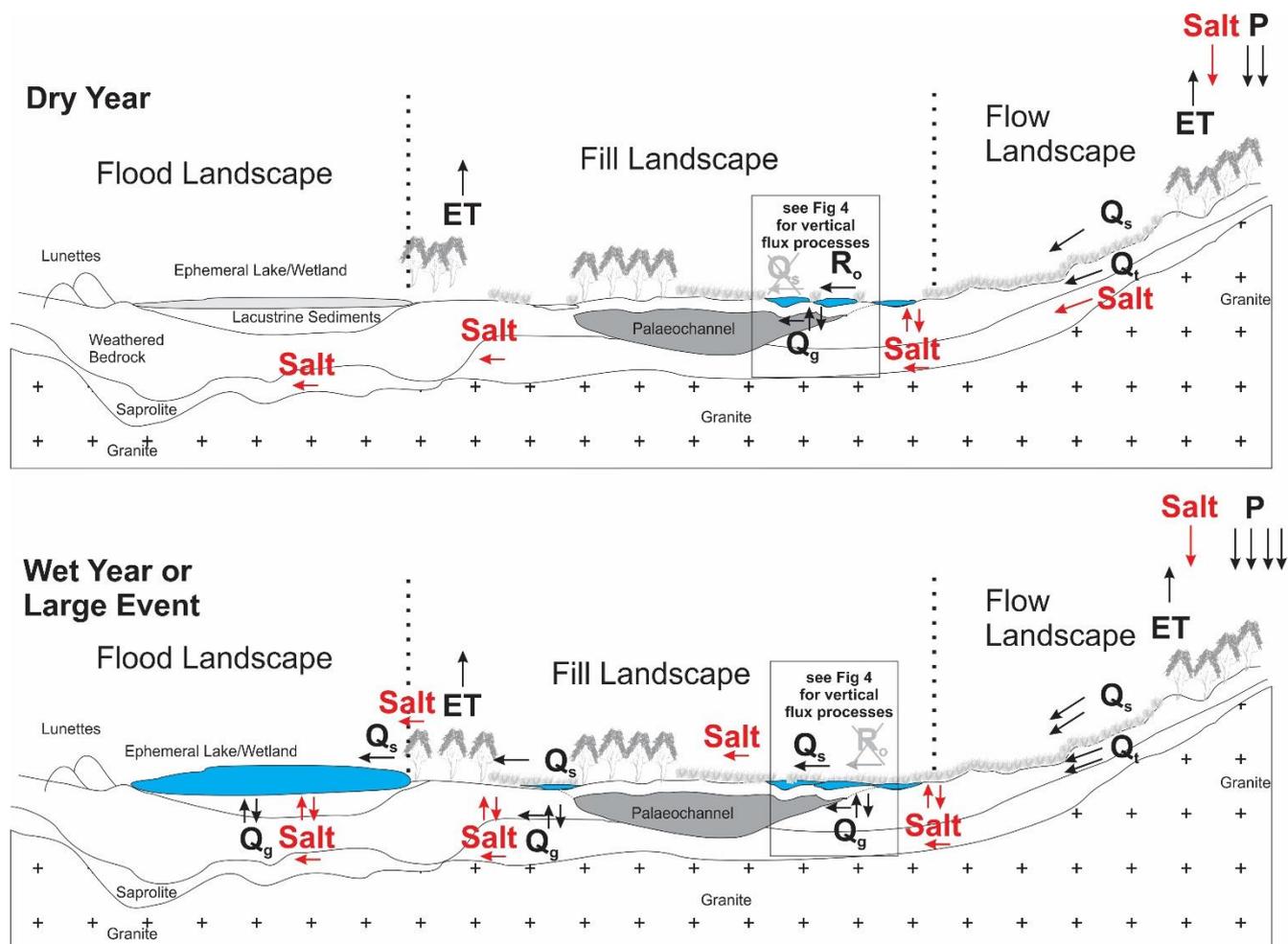
Applying a water balance approach from the long-term gauge to quantify fluxes as the basis for the hillslope-recharge model
395 of salinity, yields average annual runoff as 0.14% of rainfall. The remaining 99.86% must be accounted for by losses as
infiltration to groundwater (and/or change in storage), transpired by trees or evaporated from the surface. Whilst
evapotranspiration (ET) potential is high in this landscape (average annual Potential Pan ET 1897mm, 2008-2018 at Wickepin,
(DPIRD), unpublished data), Beringer et al. (2016) reported mean annual actual evapotranspiration (AET) at 261.7 mm yr⁻¹
(or 72 % of rainfall) for the native ecosystem Great Western Woodland OZ-Flux site that has comparable annual rainfall (361.1
400 mm yr⁻¹) to the Toolibin Catchment. Unpublished data from the cropping and farmland Ridgefield OZ-flux site suggests a
similar proportion of AET at 330 mm yr⁻¹ with average annual rainfall of 445 mm yr⁻¹ (average evapotranspiration was 74%
of rainfall, Beringer, unpublished data). Accepting AET as 72-74 % of rainfall, recharge to groundwater and change in storage
would be around 26-28 % of precipitation or around 90mm yr⁻¹. This figure is significantly higher than the upper value
405 suggested by George (1992) and George and Conacher (1993), who propose values in the range of 5.5-27 mm yr⁻¹ for cleared
agricultural land (equating to 1.5-7.5 % of rainfall at this site). If recharge was 26-28 % of precipitation, groundwater levels
in valley-floor locations would be rising at least a meter or two more per year (assuming specific yield or effective porosity
values are 0.1 to 0.05 respectively). Local or regional groundwater data certainly do not support such a high value (Bennett
and George, 2008; Mouat et al., 2008).

This paper presents evidence of significantly higher rates of internal runoff than is recorded at the long-term gauge. While
410 measured surface flow fluxes at sites from the internal gauging network only approached 5% runoff coefficients, there remains
significant uncertainty in the calculation of these figures. These are based on catchment area as defined by upslope area of a
pit-filled (coarse-resolution – 10m) DEM. This is likely to significantly over-estimate actual contributing catchment area,
particularly in agricultural landscapes with banks and farm hillslopes dams harvesting surface water, and low-gradient valley-
floors where catchment area will be dynamic with depression storage and activation (Callow et al., 2007; Callow and Smettem,
415 2009; Ryan et al., 2015). Significant surface flows not recorded in this gauging network are captured and stored on hillslopes
in farm dams (Callow and Smettem, 2009; Ryan et al., 2015). Flows reaching the valley floors are likely contributing to top-
down recharge (i.e. Site M1, stage 1), followed by likely evaporation from surface inundation on valley-floors. Within this
catchment there is a high pan potential ET through the months when surface inundation occurs (i.e. Site M1, stage 2), with
PET recorded at Wickepin in June to September respectively 57, 53, 72, 113 mm per month (DPIRD, unpublished data). This
420 flux is not accounted for in measured AET measured by flux tower sites mentioned above, that are located in vegetated stands
with no surface water inundation.



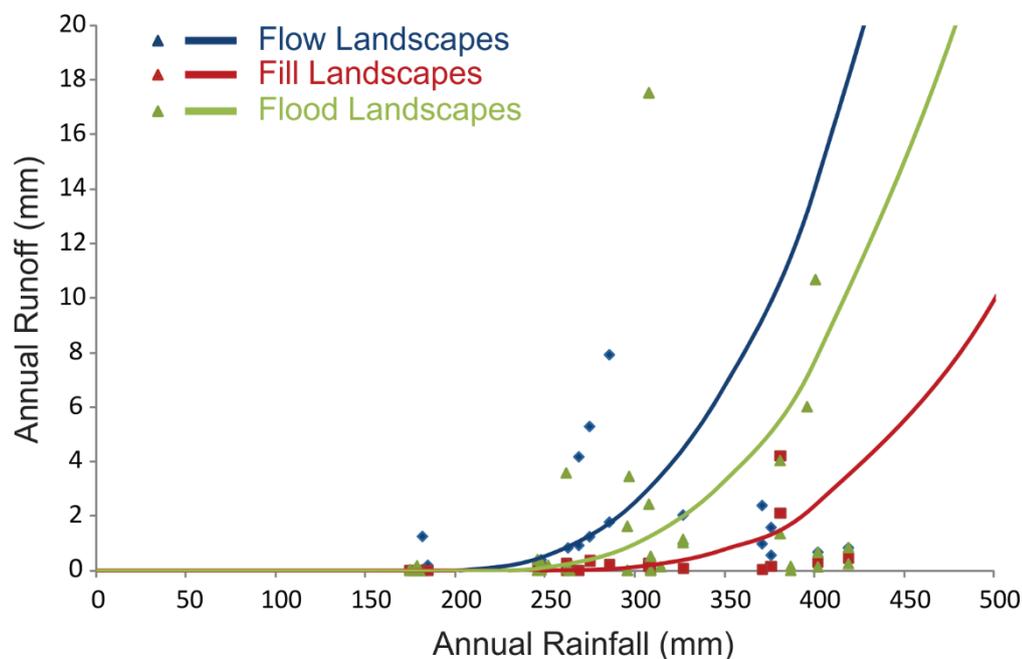
5.2 (re)Conceptualising surface water flows and dryland salinity

The results from the high-resolution gauging network and other observations, show a similar pattern of hydrological behaviour similar to work by Farmer et al. (2001, 2002), Cattlin et al. (2004) and Cattlin (2006). They applied the terms “shedding”
425 “receiving” to these landscapes, suggesting that upper shedding landscapes yielded significant volumes of fresh runoff that failed to connect and flow through the system, as it ponded in the flatter receiving landscapes. A similar though subtly different pattern is found in this study. There is an upper landscape that yields fresh runoff (termed a “flow” landscape), that contributes runoff (or runoff) to valley floor areas with high detention storage and microtopography but become seasonally activate as storage is exceeded, behaving similar as described at Site M1, Fig. 4 (“fill” landscape). Further downstream, are larger internal
430 storages and lakes (Dulbinning Lake and Toolibin Lake), that only yield flow in the wettest years or in the largest event flows (“flood” landscapes). We therefore propose this “*flow-fill-flood*” conceptualisation of the landscape water and salt flux (Fig. 6).



435 **Figure 6: Flow-Fill-Flood conceptual model of surface water and salt flux in dryland catchments, showing disconnected flow during dry years and flow connection in wet years and large events that records flow at the end-of-catchment gauge. Hydrochemical fluxes are (water flux in black, salt flux in red): P = precipitation, ET = evapotranspiration, Q_s = surface discharge or flow, Q_g = groundwater discharge or flow, and R_o = runoff storage. Salt fluxes are shown in red and show how salt is moved, concentrated and then moved down-system.**

440 To further test this conceptualisation, we use the least squares regression Tan-H method of Grayson et al.(1996) to fit rainfall/runoff curves for each of the landscape components (Fig. 7). These results support the interpretation of the hillslopes and upper landscape as a flow landscape, with higher runoff yield. Flood landscapes have the next highest runoff yield (but is biased towards infrequent larger events, so have higher yield but lower frequency). The mid-catchment, intermediate fill landscapes have very high transmission losses and relatively low runoff yield (though more frequently flow than the downstream flood landscapes).



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Figure 7: Rainfall-runoff Tah-H plot (after Grayson et al., 1996), partitioned by landscape position, identifying different hydrological behaviour in each. This indicates higher runoff from flow landscapes and lowest runoff from the fill areas due to high transmission losses through in-situ vertical recharge, with an intermediate response from flood landscapes that is influenced by these only becoming active during the greatest flows.

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The role of surface water redistribution that does not connect through a landscape (runon) is a feature of drier, flatter and semi-arid landscapes (Ludwig et al., 1997; Ludwig and Tongway, 2000; Ludwig et al., 2005). Runon to a dry and desiccated surface valley floor *fill* landscape was associated with top-down recharge of surface water (Stage 1a, Fig. 4) process noted by Teakle and Burvill in the 1930s. They linked macropores and salinity, reporting that surface salt was associated with “*the rims of crab-holes* (expression for cracking/swelling clay depressions) *where the micro-relief favours surface evaporation*” (Teakle and Burvill, 1938, p.243). While different to the pervasive hillslope-recharge model, the role of surface water as a cause of salinity is consistent with processes discussed by Teakle and Burvill (1938), Nulsen (1981), Nulsen and Henschke (1981) and Cattlin et al. (2004).

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Top-down recharge of surface water redistributed to the valley floor is consistent with lateral redistribution of runoff from lower-slopes onto the valley floors caused groundwater recharge through preferred-pathway described by Nulsen and Henschke (1981). Drake et al (2013) found macropores facilitate rapid infiltration during surface water ponding in valley floors areas in the Toolibin catchment from field inundation field trials. Barrett-Lennard (2009) and Barrett-Lennard and Callow (2009) used a 1-D model to evaluate likely flow mechanisms at site M1, and could only replicate measured recharge by parameterising macropore flow during Stage 1a and then matrix flow with preferential pathways sealed for Stage 1b (see Fig. 4). Mouat et al. (2008) noted downward hydraulic gradient in some groundwater bores in valley-floor locations closer to



465 hillslopes in this catchment. This phenomena is consistent with our reconceptualised model of hillslope surface water redistribution to the valley-floor and early-season top-down macropore (stage 1a) and matrix flow (Stage 1b) recharge.

While the sites and data presented in this study highlight the under-appreciated role of surface flows, there is still strong evidence for the role of processes as described by the hillslope-recharge model, of bottom-up groundwater flux as a cause of salinity in this landscape. At Site M1, Stage 2 (see Fig. 4) is dominated by bottom-up fluxes in late winter and spring, consistent with mechanisms of the hillslope-recharge model of salinity proposed first by Wood (1924), and work of George and Conacher (1993). This suggests that as this landscape becomes wetter through the water year, behaviour transitions towards the more pervasive model of hydrological behaviour and development of salinity. Under these conditions, hillslope recharge drives a response in these lower aquifers that drive bottom-up groundwater rise in later winter to early spring (Fig. 4, Stage 2), and is a likely important contributor to salinity in low-gradient, dryland catchments. The complexity heterogeneity of the subsurface and low lateral potential due to both (low) gradient and (fine) texture (McFarlane et al., 1989), make it challenging to qualitatively resolve the processes of lateral groundwater flow and connectivity in this landscape.

Data presented on salt yield, shows a complex response relate to the role of surface water flows and conceptualised using the flow-fill-flood model of landscape functional behaviour. In half of the years, net input into the Dulbinning Nature Reserve (fill landscape) was higher than the salt flux recorded at the long-term gauging location (flow landscape). In other years, less salt load flows into the reserve than is measured at the long-term gauge. Evidence from site M1 (Fig. 4) shows that surface inflows and inundation may facilitate vertical groundwater movement and salt diffusion to the surface in inundated areas. In lower rainfall and flow years when fill landscapes do not contribute sufficient flow to generation streamflow from flood landscapes, mobilised salts stored during inundation does not connect through the landscape, but is concentrated as surface salt scalds after evaporation and desiccation and is then available for downstream flux in subsequent years. Muirden and Coleman (2014) also reported a complex pattern of annual and event flow and salinity data, noting that summer events yielded significantly lower salinity in comparison to similar magnitude winter events. Muirden and Coleman (2014) declared that the mechanisms behind this were unclear without further research and monitoring.

5.3 Managing surface water drivers of dryland salinity

A constructed waterway was designed and built in 2009 to remove microtopography in Dulbinning Nature Reserve (fill landscape), to improve flow conveyance to stop groundwater recharge by runoff and the exchange of salts from the subsurface into the surface water. It was hypothesised that this should reduce salt yield while increasing the total flow available at the diversion structure above Toolibin Lake, allowing managers to more optimally manage the hydroperiod of Toolibin Lake (Hipsey et al., 2011; Coletti et al., 2013). Before construction, flows in a wetter year (2008, decile 8 rainfall) had a 60 % transmission loss (Fig. 3) through Dulbinning Nature Reserve. This is consistent with the results of Cattlin et al. (2004) who reported in 60-100% transmission losses during events between 2000 and 2003, and Callow et al. (2010) who reported an average 50% of runoff volume lost in the reserve across the gauge record and prior to waterway construction. After construction, Muirden and Coleman (2014) reported a 25 % increase in flow volume yielded through this part of the landscape.



The analysis of salt load transmitted post-construction found that the streamflow salinity reaching Toolibin Lake was 20 % lower when compared to similar magnitude events before construction. The combination of increased flow yield and lower
500 flow salinity results in significant reduction of total salt contributed downstream.

Much effort in addressing salinity has been aimed at increasing perennial vegetation in the landscape (Hatton and Nulsen, 1999). Tree planting has been found to provide benefits in areas of higher rainfall and on sandplain seep sites, where recharge management has delivered direct impacts in reducing groundwater levels and expansion saline areas (Bell et al., 1990; George et al., 1999; Bennett and George, 2008). For low-gradient and lower in lower rainfall zones (<600 mm yr⁻¹), there has been
505 little to no evidence of revegetation impacts on groundwater at the scale it has been implemented at (George et al., 1999; Johnsen et al., 2008), but remains a popular approach in attempts to combat salinity and provide biodiversity and ecosystem services benefits (Cramer and Hobbs, 2002; Halse et al., 2003; Pannell, 2008). Ryan et al. (2015) provides an interesting paradigm to consider in the context of this work on how hillslope vegetation and surface water management can be integrated. In the valley-floor, the broad-based channel is a high-cost intervention but offers a potential to address some processes causing
510 salinity, and in some parts of the landscape. Assessing long-term vegetation recovery surrounding the channel was beyond the scope of this paper, but a worthy of future research.

The constructed waterway intervention is very different to the deep drainage approach used to combat rising groundwater salinity in valley-floor locations in the Wheatbelt region of Western Australia (Coles et al., 1999; Pannell, 2001; Ali et al., 2004; Pannell and Ewing, 2004; Barrett-Lennard et al., 2005). These are based on digging a ditch or drain to a depth of around
515 2m to intercept groundwater and dispose of the saline groundwater effluent downstream (Ali et al., 2004). Deep drainage offers limited or no economic return on investment for broadacre farming (Pannell, 2001; Ali et al., 2004; Pannell and Ewing, 2004), and has detrimental downstream environment impacts, with discharge often acidic (pH 1.9-3.8) and high in salinity (measured as up to 147,000 mg l⁻¹ or 4 ½ times seawater salinity) (Stewart et al., 2009). Deep drains can exacerbate waterlogging and salinity through the processes identified by this study, as spoil or the removed material is dumped at the sides of the drain and
520 causes ponding of surface water. A major cost, but important feature in this targeted intervention was the removal of excavated soil material (used to fill low-lying areas on adjacent land). The constructed waterway was designed to convey only low to moderate flow events (~1:3 yr), where lateral outflow could then return back into the channel as the flood dissipates. The performance of the broad-based channel provides further validation of the role that surface water redistribution plays in the development of salinity in low-gradient drylands.

525 6 Conclusion

This paper presents a range of evidence that surface water flows play an important role in causing salinity in low-gradient drylands, conceptualising this as *flow-fill-flood* functional behaviour. Much of the generation and internal redistribution of surface flows are not recorded at the long-term gauging location in this catchment. This masks the important role that (disconnected) surface flows have in this and other low-gradient dryland catchments, including as a contributor to land



- 530 degradation by dryland salinity. It is shown that surface flows fill landscape detention storages, and there is top-down recharge in these locations. Inundation creates a potential for vertical diffusion of salts that can evapo-concentrate at the surface and degrade these areas, or impact downstream systems when depression storage is exceeded. The broad-based channel management intervention to address surface water processes and *flow-fill-flood* functional behaviour has been shown to increase the yield of water, and to decrease the salinity of streamflow and downstream salt yield.
- 535 Catchments in the low-gradient drylands have elements of hydrological behaviour in common with high rainfall, steeper-sloped hydrologically connected catchments of the temperate, tropical and sub-tropical areas, but are equally influenced by processes common with dry, flat and disconnected smooth plainlands, rangelands, semi-arid regions and deserts. Beyond this study region, the new insight from the “*flow-fill-flood*” understanding of dryland salinity further demonstrates the importance of testing and reassessing how rainfall and topography interact across a range of settings in time and space to moderate
- 540 hydrological processes. It is critical to appreciate and question how catchment dynamics in the context of wet-dry, steep-flat, connected-disconnected and related important subtly of how surface and groundwater processes drive hydrology, and in this case land degradation by dryland salinity. Successful management interventions need to address the specific causes of dryland salinity, you cannot manage what you do not understand.



545 7 Author contribution

NC designed the field experiment and collected data with other acknowledged assistance, RV supported field interventions. NC led data analyses, MH and RV contributed to methodological development. NC led manuscript writing with significant contributions from MH and RV.

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555 and P Muirden is acknowledged for his work in improving the quality of these raw data. The new waterway was constructed by DPaW under the Natural Diversity Recovery Catchments program. A Barrett-Lennard completed a B Eng Hons thesis and data reworked from that study forms the basis for Figure 4. Landholders in the Toolibin Lake catchment, are thanked for permission to establish and access field sites on their properties. We acknowledge the Traditional Owners of the land on which this research occurred and pay our respects to their Elders, past and present.

560 9 References

- Abrisqueta, J. M., Plana, V., Mounzer, O. H., Mendez, J., and Ruiz-Sanchez, M. C.: Effects of soil tillage on runoff generation in a Mediterranean apricot orchard, *Agricultural Water Management*, 93, 11-18, <https://doi.org/10.1016/j.agwat.2007.06.002>, 2007.
- Ali, R., Hatton, T., George, R., Byrne, J., and Hodgson, G.: Evaluation of the impacts of deep open drains on groundwater levels in the wheatbelt of Western Australia, *Australian Journal of Agricultural Research*, 55, 1159-1171, <https://doi.org/10.1071/ar04068>, 2004.
- Bann, G. R., and Field, J. B.: Dryland salinity in south east Australia: A localised surface water and soil degradation process?, *Regolith 2006 - Consolidation and Dispersion of Ideas*, 2006a.
- Bann, G. R., and Field, J. B.: Dryland salinity in south east Australia: Which scenario makes more sense?, *AESC2006*,
570 Melbourne, Australia, 2006b.
- Barrett-Lennard, A.: Surface water ponding on low lying valley floors in south-western Australia: interactions with groundwater and its role in secondary dryland salinity, BEng Hons, School of Environmental Systems Engineering, The University of Western Australia, Perth, Western Australia, 2009.



- Barrett-Lennard, A., and Callow, J. N.: Surface water ponding, in-situ vertical recharge and salinity in low-gradient valleys:
575 Toolibin Lake, southwestern Australia., OzWater Conference, Melbourne, Australia, 2009.
- Barrett-Lennard, E. G., George, R. J., Hamilton, G., Norman, H. C., and Masters, D. G.: Multi-disciplinary approaches suggest profitable and sustainable farming systems for valley floors at risk of salinity, *Australian Journal of Experimental Agriculture*, 45, 1415–1424, <https://doi.org/10.1071/ea04157>, 2005.
- Barron, O., Silberstein, R., Ali, R., Donohue, R., McFarlane, D. J., Davies, P., Hodgson, G., Smart, N., and Donn, M.: Climate
580 change effects on water-dependent ecosystems in south-western Australia, *Journal of Hydrology*, 434–435, 95–109, <https://doi.org/10.1016/j.jhydrol.2012.02.028>, 2012.
- Bauer, P., Gumbrecht, T., and Kinzelbach, W.: A regional coupled surface water/groundwater model of the Okavango Delta, Botswana, *Water Resour. Res.*, 42, W04403, <https://doi.org/10.1029/2005wr004234>, 2006.
- Beard, J. S.: Palaeodrainage and the geomorphic evolution of passive margins in Southwestern Australia, *Zeitschrift Fur
585 Geomorphologie*, 47, 273–288, 2003.
- Bell, R. W., Schofield, N. J., Loh, I. C., and Bari, M. A.: Groundwater response to reforestation in the Darling Range of Western Australia, *Journal of Hydrology*, 115, 297–317, [https://doi.org/10.1016/0022-1694\(90\)90211-F](https://doi.org/10.1016/0022-1694(90)90211-F), 1990.
- Bennett, D., and Macpherson, D. K.: A history of salinity in Western Australia important (and some unimportant) dates, Update of: CSIRO, Division of Groundwater Research, Technical memorandum 83/1, Perth, Western Australia, 2002.
- 590 Bennett, D., and George, R. J.: Long term monitoring of groundwater levels at 24 sites in Western Australia shows that integrated farm forestry systems have little impact on salinity, 2nd International Salinity Forum: Salinity, water and society-global issues, local action, Adelaide, Australia, 2008,
- Beringer, J., Hutley, L. B., McHugh, I., Arndt, S. K., Campbell, D., Cleugh, H. A., Cleverly, J., Resco de Dios, V., Eamus, D., Evans, B., Ewenz, C., Grace, P., Griebel, A., Haverd, V., Hinko-Najera, N., Huete, A., Isaac, P., Kanniah, K., Leuning, R.,
595 Liddell, M. J., Macfarlane, C., Meyer, W., Moore, C., Pendall, E., Phillips, A., Phillips, R. L., Prober, S. M., Restrepo-Coupe, N., Rutledge, S., Schroder, I., Silberstein, R., Southall, P., Yee, M. S., Tapper, N. J., van Gorsel, E., Vote, C., Walker, J., and Wardlaw, T.: An introduction to the Australian and New Zealand flux tower network – OzFlux, *Biogeosciences*, 13, 5895–5916, <https://doi.org/10.5194/bg-13-5895-2016>, 2016.
- Bonell, M., and Williams, J. D.: A review of hydrology research within the open eucalypt woodlands of tropical semiarid
600 Australia: A possible source of baseline information for the West African Sahel, *Sécheresse*, 20, 31–47, 2009.
- Bowman, S., and Ruprecht, J. K.: Blackwood River flood risk study, Surface Water Hydrology, Science and Evaluation, Water and Rivers Commission, Perth, Western Australia. Report: SWH 29, 2000.
- Bracken, L. J., and Croke, J. C.: The concept of hydrological connectivity and its contribution to understanding runoff-dominated geomorphic systems, *Hydrological Processes*, 21, 1749–1763, <https://doi.org/10.1002/hyp.6313>, 2007.
- 605 Bracken, L. J., Wainwright, J., Ali, G. A., Tetzlaff, D., Smith, M. W., Reaney, S. M., and Roy, A. G.: Concepts of hydrological connectivity: Research approaches, pathways and future agendas, *Earth-Science Reviews*, 119, 17–34, <http://dx.doi.org/10.1016/j.earscirev.2013.02.001>, 2013.



- Callow, J. N., and Smettem, K. R. J.: Channel response to a new hydrological regime in southwestern Australia, *Geomorphology*, 84, 254-276, <https://doi.org/10.1016/j.geomorph.2006.01.043>, 2007.
- 610 Callow, J. N., Van Niel, K. P., and Boggs, G. S.: How does modifying a DEM to reflect known hydrology affect subsequent terrain analysis?, *Journal of Hydrology*, 332, 30-39, <https://doi.org/10.1016/j.jhydrol.2006.06.020>, 2007.
- Callow, J. N., Pope, T. I., and Coles, N. A.: Surface water flow redistribution processes: Toolibin Lake biodiversity recovery catchment, Report by the ARWA – Centre for Ecohydrology for the Department of Environment and Conservation. Perth, Western Australia CER 07/01 – SESE129, 2008.
- 615 Callow, J. N., and Smettem, K. R. J.: The effect of farm dams and constructed banks on hydrologic connectivity and runoff estimation in agricultural landscapes, *Environmental Modelling & Software*, 24, 959-968, <https://doi.org/10.1016/j.envsoft.2009.02.003>, 2009.
- Callow, J. N.: Understanding patterns of vegetation degradation at meaningful scales within saline landscapes, *Ecohydrology*, 4, 841-854, <https://doi.org/10.1002/eco.190>, 2011.
- 620 Callow, J. N., and Clifton, J.: *Globalised Agriculture, Development and the Environment, Globalisation, Agriculture and Development: Perspectives from the Asia-Pacific*, edited by: Tonts, M. J., and Siddique, M. A. B., Elgar, 2011.
- Callow, J. N.: Potential for vegetation-based river management in dryland, saline catchments, *River Research and Applications*, 28, 1072–1092, <https://doi.org/10.1002/rra.1506>, 2012.
- Cattlin, T., Stanton, D., Farmer, D. L., and Coles, N. A.: Surface water management strategy - Report for the Shire of Yilgarn. , Engineering Water Management Group Technical Report, Department of Agriculture Western Australia, South Perth, Western Australia, 2002.
- 625 Cattlin, T., and Farmer, D.: Hydrological processes of the Wheatbelt region of Western Australia, *Proceedings of the 13th International Soil Conservation Organisation Conference - Conserving Soil and Water for Society: Sharing Solutions ISCO 2004*, Brisbane Australia, 2004.
- 630 Cattlin, T., Farmer, D. L., Coles, N. A., and Stanton, D.: *Surface Water Assessment for the Toolibin Lake Recovery Catchment*, Engineering Water Management Group, Department of Agriculture Western Australia., Perth, Australia, 2004.
- Cattlin, T.: The impact of redistributed surface water and spatially distributed recharge on water quality decline in the Toolibin Lake catchment: a modelled approach to process management, MSc, National Centre for Groundwater Manegment, University of Technology, Sydney, 2006.
- 635 Ceballos, A., and Schnabel, S.: Hydrological behaviour of a small catchmnet in the dehesa landuse system (Extremadura, SW Spain), *Journal of Hydrology*, 210, 146-160, 1998.
- Clarke, J. D. A.: Evolution of the Lefroy and Cowan palaeodrainage channels, Western Australia, *Australian Journal of Earth Sciences*, 41, 55-68, 1994.
- Coles, N. A., George, R. J., and Bathgate, A.: An assessment of the efficacy of deep drains construction in the wheatbelt of Western Australia, *Agriculture Western Australia, Perth, Western Australia Miscellaneous Bulletin 4391*, 1999.
- 640



- Coletti, J. Z., Hinz, C., Vogwill, R., and Hipsey, M. R.: Hydrological controls on carbon metabolism in wetlands, *Ecological Modelling*, 249, 3-18, <http://dx.doi.org/10.1016/j.ecolmodel.2012.07.010>, 2013.
- Commander, P., Schoknecht, N., Verboom, B., and Caccetta, P. A.: The geology, physiography and soils of wheatbelt valleys, *Dealing with salinity in Wheatbelt valleys: processes, prospects and practical options*, Merredin, Western Australia, 2001,
- 645 Conacher, A. J., and Conacher, J.: *Rural land degradation in Australia*, Oxford University Press, Melbourne, 170 pp., 1995.
- Conacher, A. J., and Sala, M.: *Land degradation in Mediterranean environments of the world: nature and extent, causes and solutions*, John Wiley and Sons, Chichester, 491 pp., 1998.
- Costa, A. C., Foerster, S., de Araújo, J. C., and Bronstert, A.: Analysis of channel transmission losses in a dryland river reach in northeastern Brazil using streamflow series, groundwater level series and multi-temporal satellite data, *Hydrological Processes*, 27, 1046-1060, <https://doi.org/10.1002/hyp.9243>, 2012.
- 650 Cramer, V. A., and Hobbs, R. J.: Ecological consequences of altered hydrological regimes in fragmented ecosystems in southern Australia: Impacts and possible management responses, *Austral Ecology*, 27, 546-564, <https://doi.org/10.1046/j.1442-9993.2002.01215.x>, 2002.
- Drake, P. L., Coleman, B. F., and Vogwill, R.: The response of semi-arid ephemeral wetland plants to flooding: linking water use to hydrological processes, *Ecohydrology*, 6, 852-862, <https://doi.org/10.1002/eco.1309>, 2013.
- 655 Dunkerley, D.: Effects of rainfall intensity fluctuations on infiltration and runoff: rainfall simulation on dryland soils, Fowlers Gap, Australia, *Hydrological Processes*, 26, 2211-2224, <https://doi.org/10.1002/hyp.8317>, 2011.
- Eamus, D., Hatton, T., Cook, P., and Colvin, C.: *Ecohydrology: Vegetation Function, Water and Resource Management*, CSIRO Publishing, Canberra, 2006.
- 660 Farmer, D., Stanton, D., and Coles, N. A.: *Surface Water Assessment and Recommendations for the Lake Bryde Recovery Catchment*, Engineering Water Management Group, Department of Agriculture, South Perth, Western Australia, 2001.
- Farmer, D., Stanton, D., and Coles, N. A.: *Lake Bryde Recovery Catchment Surface Water Assessment and Recommendations*, Engineering Water Management Group, Department of Agriculture Western Australia. Report prepared for the Department of Conservation and Land Management, Perth, Western Australia, 2002.
- 665 Ferdowsian, R., George, R., Lewis, F., McFarlane, D. J., Short, R., and Speed, R.: The extent of dryland salinity in Western Australia, 4th National Conference and Workshop on the Productive Use and Rehabilitation of Saline Lands (PURSL), Albany, Western Australia, 1996,
- George, R.: Estimating and modifying the effects of agricultural development on the groundwater balance of large wheatbelt catchments, Western Australia, *Journal of Applied Hydrogeology*, 1, 41-54, 1992.
- 670 George, R., and Conacher, A. J.: Mechanisms responsible for streamflow generation on a small, salt-affected and deeply weathered hillslope., *Earth Surface Processes and Landforms*, 18, 291-309, 1993.
- George, R. J.: Reclaiming sandplain seeps by intercepting perched groundwater with eucalypts, *Land Degradation and Development*, 2, 13-25, 1990.



- George, R. J., Nulsen, R. A., Ferdowsian, R., and Raper, G. P.: Interactions between trees and groundwaters in recharge and
675 discharge areas - A survey of Western Australian sites, *Agricultural Water Management*, 39, 91-113, 1999.
- George, R. J., Speed, R. J., Simons, J. A., Smith, R. H., Ferdowsian, R., Raper, G. P., and Bennett, D.: Long-term groundwater
trends and their impact on the future extent of dryland salinity in Western Australia in a variable climate., 2nd International
Salinity Forum: Salinity, water and society-global issues, local action, Adelaide, Australia, 2008,
- Ghassemi, F., Jakeman, A. J., and Nix, H. A.: Salinisation of land and water resources: human causes, extent, management
680 and case studies, University of New South Wales Press, Sydney, Australia, 526 pp., 1995.
- Gifford, G. F.: Rangeland hydrology in Australia - A brief review, *Australian Rangeland Journal*, 1, 150-166, 1978.
- Grayson, R., Argent, R. M., Nathan, R. J., McMahon, T. A., and Mein, R. G.: Hydrological recipes: Estimation techniques in
Australian hydrology, Cooperative Research Centre for Catchment Hydrology, Monash University, Victoria, Australia, 125
pp., 1996.
- 685 Halse, S. A., Ruprecht, J. K., and Pinder, A. M.: Salinisation and prospects for biodiversity in rivers and wetlands of south-
west Western Australia, *Australian Journal of Botany*, 51, 673-688, <https://doi.org/10.1071/BT02113>, 2003.
- Hatton, T., and Salama, R. B.: Is it feasible to restore the salinity-affected rivers of the Western Australian wheatbelt?,
Proceedings of Second Australian Stream Management Conference, Adelaide, 1999, 313-317,
- Hatton, T. J., and Nulsen, R. A.: Towards achieving functional ecosystem mimicry with respect to water cycling in southern
690 Australian agriculture, *Agroforestry Systems*, 45, 203-214, 1999.
- Hatton, T. J., Ruprecht, J., and George, R. J.: Preclearing hydrology of the Western Australia wheatbelt: Target for the future?,
Plant and Soil, 257, 341-356, 2003.
- HilleRisLambers, R., Rietkerk, M., van den Bosch, F., Prins, H. H. T., and de Kroon, H.: Vegetation pattern formation in semi-
arid grazing systems, *Ecology*, 82, 50-61, [https://doi.org/10.1890/0012-9658\(2001\)082\[0050:vpfisa\]2.0.co;2](https://doi.org/10.1890/0012-9658(2001)082[0050:vpfisa]2.0.co;2), 2001.
- 695 Hingston, F. J., and Gailitis, V.: The geographic variation of salt precipitated over Western Australia, *Australian Journal of
Soil Research*, 14, 319-335, 1976.
- Hipsey, M. R., Vogwill, R., Farmer, D., and Busch, B. D.: A multi-scale ecohydrological model for assessing floodplain
wetland response to altered flow regimes, 19th International Congress on Modelling and Simulation, Perth, Australia, 2011.
- Hrachowitz, M., Savenije, H. H. G., Blöschl, G., McDonnell, J. J., Sivapalan, M., Pomeroy, J. W., Arheimer, B., Blume, T.,
700 Clark, M. P., Ehret, U., Fenicia, F., Freer, J. E., Gelfan, A., Gupta, H. V., Hughes, D. A., Hut, R. W., Montanari, A., Pande,
S., Tetzlaff, D., Troch, P. A., Uhlenbrook, S., Wagener, T., Winsemius, H. C., Woods, R. A., Zehe, E., and Cudennec, C.: A
decade of Predictions in Ungauged Basins (PUB)—a review, *Hydrological Sciences Journal*, 58, 1198-1255,
<https://doi.org/10.1080/02626667.2013.803183>, 2013.
- Johnsen, C., George, R., Clarke, C., Harper, R., and Bren, L.: Groundwater Response To Partial Plantings On Discharge Zones
705 At Five Sites In The South West Of Western Australia, Second International Salinity Forum, Adelaide, Australia, 2008,
- Johnstone, M. H., Lowry, D. C., and Quilty, P. G.: The geology of southwestern Australia - a review, *Journal of the Royal
Society of Western Australia*, 56, 5-15, 1973.



- Jones, C. E.: The Great Salinity Debate: Part 1 Controlling the salinisation process, *Stipa Newsletter*, 14, 4-6, 2000a.
- Jones, C. E.: The Great Salinity Debate: Part 2 Why the recharge-discharge model is fundamentally flawed, *Stipa Newsletter*,
710 14, 6-11, 2000b.
- Knighton, A. D., and Nanson, G. C.: An event-based approach to the hydrology of arid zone rivers in the Channel Country of Australia, *Journal of Hydrology*, 254, 102-123, [http://dx.doi.org/10.1016/S0022-1694\(01\)00498-X](http://dx.doi.org/10.1016/S0022-1694(01)00498-X), 2001.
- Koohafkan, P., and Stewart, B. A.: Drylands, people and land use, in: *Water and Cereals in Drylands*, edited by: Koohafkan, P., and Stewart, B. A., The Food and Agriculture Organization of the United Nations and Earthscan, London, 2008.
- 715 Ludwig, J. A., Tongway, D. J., Freudenberger, D. O., Noble, J. C., and Hodgkinson, K. C.: Landscape ecology, function and management: principles from Australia's rangelands, CSIRO Publishing, Melbourne, Australia, 1997.
- Ludwig, J. A., and Tongway, D. J.: Viewing rangelands as landscape systems, in: *Rangeland desertification*, edited by: Arnalds, O., and Archer, S., Kluwer Academic Publishers, Dordrecht, The Netherlands, 39-52, 2000.
- Ludwig, J. A., Wilcox, B. P., Breshears, D. D., Tongway, D. J., and Imeson, A. C.: Vegetation Patches and Runoff-Erosion
720 as Interacting Ecohydrological Processes in Semiarid Landscapes, *Ecology*, 86, 288-297, <https://doi.org/10.1890/03-0569>, 2005.
- Mann, E. A.: Does clearing increase salt in ground, *Journal of Agriculture, Western Australia*, 15, 193, 1907.
- McDonnell, J. J., and Woods, R.: On the need for catchment classification, *Journal of Hydrology*, 299, 2-3, <http://dx.doi.org/10.1016/j.jhydrol.2004.09.003>, 2004.
- 725 McFarlane, D., Engel, R., and Ryder, A.: The location of recharge areas responsible for valley salinity in the Lake Toolibin Catchment, Western Australia, *Groundwater Recharge*, 255-267, 1989.
- McFarlane, D., Stone, R., Martens, S., Thomas, J., Silberstein, R., Ali, R., and Hodgson, G.: Climate change impacts on water yields and demands in south-western Australia, *Journal of Hydrology*, 475, 488-498, <https://doi.org/10.1016/j.jhydrol.2012.05.038>, 2012.
- 730 McGrath, G. S., Paik, K., and Hinz, C.: Microtopography alters self-organized vegetation patterns in water-limited ecosystems, *Journal of Geophysical Research: Biogeosciences*, 117, G03021, <https://doi.org/10.1029/2011jg001870>, 2012.
- McMillan, H. K., Clark, M. P., Bowden, W. B., Duncan, M., and Woods, R. A.: Hydrological field data from a modeller's perspective: Part 1. Diagnostic tests for model structure, *Hydrological Processes*, 25, 511-522, <https://doi.org/10.1002/hyp.7841> 2011.
- 735 Mouat, N. C., George, R. J., Smettem, K. R. J., and Gilkes, R. J.: Identifying dominant catchment properties for predicting dryland salinity development in the Western Australian wheat belt, 2nd International Salinity Forum: Salinity, water and society-global issues, local action, Adelaide, Australia, 2008,
- Muirden, P., Pen, L., and Leybourne, M.: Stream and catchment hydrology in south west Western Australia, Department of Environment, Perth, Western Australia Report No.RR19, 2003.
- 740 Muirden, P., and Coleman, S.: The Toolibin natural diversity recovery catchment review of surface water monitoring, Report for the Department of Parks and Wildlife, WA Government, Perth Western Australia, 2014.



- Mulcahy, M. J.: Landscapes, laterites and soils in southwestern Australia, in: *Landform studies from Australia and New Guinea*, edited by: Jennings, J. N., and Mabbutt, J. A., Australian National University Press, Canberra, 1967.
- Nanson, G. C., Tooth, S., and Knighton, A. D.: A global perspective on dryland rivers: perceptions, misconceptions and distinctions, in: *Dryland rivers: hydrology and geomorphology of semi-arid channels*, edited by: Bull, L. J., and Kirkby, M. J., Wiley, Chichester, 17-54, 2002.
- 745 Neal, B. P., Nathan, R. J., Schreider, S., and Jakeman, A. J.: Identifying the Separate Impact of Farm Dams and Land Use Changes on Catchment Yield, *Australian Journal of Water Resources*, 5, 165-176, 2001.
- Nicolau, J. M., Solé-Benet, A., Puigdefábregas, J., and Gutiérrez, L.: Effects of soil and vegetation on runoff along a catena in semi-arid Spain, *Geomorphology*, 14, 297-309, [https://doi.org/10.1016/0169-555x\(95\)00043-5](https://doi.org/10.1016/0169-555x(95)00043-5), 1996.
- 750 Nielsen, D. L., Brock, M. A., Rees, G., N., and Baldwin, D. S.: Effects of increasing salinity on freshwater ecosystems in Australia, *Australian Journal of Botany*, 51, 655-665, <https://doi.org/10.1071/BT02115>, 2003.
- Nulsen, R. A.: Critical depth to saline groundwater in non-irrigated situations, *Australian Journal of Soil Research*, 19, 83-86, <https://doi.org/10.1071/SR9810083>, 1981.
- 755 Nulsen, R. A., and Henschke, C. J.: Groundwater systems associated with secondary salinity in Western Australia, *Agricultural Water Management*, 4, 173-186, [https://doi.org/10.1016/0378-3774\(81\)90049-4](https://doi.org/10.1016/0378-3774(81)90049-4), 1981.
- Pannell, D.: Dryland salinity: economic, scientific, social and policy dimensions, *The Australian Journal of Agricultural and Resource Economics*, 45, 517-546, 2001.
- Pannell, D., and Ewing, M. A.: Managing secondary dryland salinity: Options and challenges, *Proceedings, 4th International Crop Science Congress*, 2004,
- 760 Pannell, D.: Public Benefits, Private Benefits, and Policy Mechanism Choice for Land-Use Change for Environmental Benefits, *Land Economics*, 84, 225-240, 2008.
- Peck, A. J., and Hatton, T.: Salinity and the discharge of salts from catchments in Australia, *Journal of Hydrology*, 272, 191-202, 2003.
- 765 Pen, L. J.: *Managing our rivers: a guide to the nature and management of the streams of south-west Western Australia*, Water and Rivers Commission, East Perth, Western Australia, 1999.
- Powell, D. M.: Dryland Rivers: Processes and Forms, in: *Geomorphology of Desert Environments*, 333-373, 2009.
- Ruprecht, J. K., and Schofield, N. J.: Analysis of streamflow generation following deforestation in southwestern Western Australia, *Journal of Hydrology*, 105, 1-17, 1989.
- 770 Ruprecht, J. K., and Schofield, N. J.: Effects of partial deforestation on hydrology and salinity in high salt storage landscapes. I. Extensive block clearing, *Journal of Hydrology*, 129, 19-38, 1991.
- Ruprecht, J. K., and Stoneman, G. L.: Water yield issues in the jarrah forest of south-western Australia, *Journal of Hydrology*, 150, 369-391, 1993.
- Ryan, J. G., McAlpine, C. A., Ludwig, J. A., and Callow, J. N.: Modelling the Potential of Integrated Vegetation Bands (IVB) to Retain Stormwater Runoff on Steep Hillslopes of Southeast Queensland, Australia, *Land*, 4, 711-736, 2015.
- 775



- Smettem, K., and Callow, N.: Impact of Forest Cover and Aridity on the Interplay between Effective Rooting Depth and Annual Runoff in South-West Western Australia, *Water*, 6, 2539-2551, 2014.
- Smettem, K. R. J., Waring, R. H., Callow, J. N., Wilson, M., and Mu, Q.: Satellite-derived estimates of forest leaf area index in southwest Western Australia are not tightly coupled to interannual variations in rainfall: implications for groundwater decline in a drying climate, *Global Change Biology*, 19, 2401-2412, <https://doi.org/10.1111/gcb.12223>, 2013.
- 780 Stewart, B., Strehlow, K., and Davis, J.: Impacts of deep open drains on water quality and biodiversity of receiving waterways in the Wheatbelt of Western Australia, *Hydrobiologia*, 619, 103-118, <https://doi.org/10.1007/s10750-008-9603-x>, 2009.
- Takken, I., Govers, G., Steegen, A., Nachtergaele, J., and Guérif, J.: The prediction of runoff flow directions on tilled fields, *Journal of Hydrology*, 248, 1-13, [https://doi.org/10.1016/S0022-1694\(01\)00360-2](https://doi.org/10.1016/S0022-1694(01)00360-2), 2001.
- 785 Teakle, L. J. H., and Burvill, G. H.: The movement of soluble salts in soils under light rainfall conditions, *Journal of Agriculture of Western Australia*, 15, 218-245, 1938.
- Thornes, J. B.: Catchment and Channel Hydrology, in: *Geomorphology of Desert Environments*, edited by: Parsons, A. J., and Abrahams, A. D., Springer Netherlands, 2009.
- Tooth, S.: Process, form and change in dryland rivers: a review of recent research, *Earth Science Reviews*, 51, 67-107, [https://doi.org/10.1016/S0012-8252\(00\)00014-3](https://doi.org/10.1016/S0012-8252(00)00014-3), 2000.
- 790 Turnbull, L., Wilcox, B. P., Belnap, J., Ravi, S., D'Odorico, P., Childers, D., Gwenzi, W., Okin, G., Wainwright, J., Caylor, K. K., and Sankey, T.: Understanding the role of ecohydrological feedbacks in ecosystem state change in drylands, *Ecohydrology*, 5, 174-183, <https://doi.org/10.1002/eco.265>, 2012.
- van de Graaff, W. J. E., Crowe, R. W. A., Bunting, J. A., and Jackson, M. J.: Relict Early Cainozoic drainages in arid Western Australia, *Zeitschrift Fur Geomorphologie*, 21, 379-400, 1977.
- 795 Verboom, W.: *Soils of the Toolibin Lake Catchment*, Agriculture Western Australia, Perth, Australia, 2003.
- Wagener, T., Sivapalan, M., Troch, P., and Woods, R.: Catchment Classification and Hydrologic Similarity, *Geography Compass*, 1, 901-931, <https://doi.org/10.1111/j.1749-8198.2007.00039.x>, 2007.
- Walker, K. F., Sheldon, F., and Puckridge, J. T.: A perspective on dryland river ecosystems, *Regulated Rivers: Research & Management*, 11, 85-104, 1995.
- 800 Wang, L., D'Odorico, P., Evans, J. P., Eldridge, D. J., McCabe, M. F., Caylor, K. K., and King, E. G.: Dryland ecohydrology and climate change: critical issues and technical advances, *Hydrol. Earth Syst. Sci.*, 16, 2585-2603, <https://doi.org/10.5194/hess-16-2585-2012>, 2012.
- Watson, A. N.: The clearing history of the Toolibin area and some of its effects, Compiled for the Northern Arthur River Rehabilitation Committee, 1978.
- 805 Wilcox, B. P., and Newman, B. D.: Ecohydrology of Semiarid Landscapes, *Ecology*, 86, 275-276, <https://doi.org/10.1890/04-0631>, 2005.
- Wood, W. E.: Increase of salt in soil and streams following the destruction of the native vegetation, *Journal of the Royal Society of Western Australia*, X, 35-47, 1924.



- 810 Wood, W. E., and Wilshire, N. T. M.: Salinity of rain in Western Australia, *Journal of the Royal Society of Western Australia*, XV, xxii-xxx, 1928.