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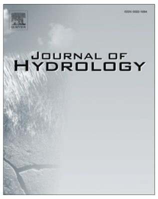

Where does all the water go? Partitioning water transmission losses in a data-sparse, multi-channel and low-gradient dryland river system using modelling and remote sensing

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SUMMARY

Drylands cover approximately one-third of the Earth's surface, are home to nearly 40% of the Earth's population and are characterised by limited water resources and ephemeral river systems with an extremely variable flow regime and high transmission losses. These losses include actual evaporation, infiltration to the soil and groundwater and residual (terminal) water remaining after flood events. These critical components of the water balance of dryland river systems remain largely unknown due to the scarcity of observational data and the difficulty in accurately accounting for the flow distribution in such large multi-channel floodplain systems. While hydrodynamic models can test hypotheses concerning the water balance of infrequent flood events, the scarcity of flow measurement data inhibits model calibration, constrains model accuracy and therefore utility. This paper provides a novel approach to this problem by combining modelling, remotely-sensed data, and limited field measurements, to investigate the partitioning of flood transmissions losses based on seven flood events between February 2006 and April 2012 along a 180 km reach of the Diamantina River in the Lake Eyre Basin, Australia. Transmission losses were found to be high, on average 46% of total inflow within 180 km reach segment or 7 GL/km (range: 4–10 GL/km). However, in 180 km reach, transmission losses vary non-linearly with flood discharge, with smaller flows resulting in higher losses (up to 68%), which diminish in higher flows (down to 24%) and in general there is a minor increase in losses with distance downstream. Partitioning these total losses into the major components shows that actual evaporation was the most significant component (21.6% of total inflow), followed by infiltration (13.2%) and terminal water storage (11.2%). Lateral inflow can be up to 200% of upstream inflow (mean = 86%) and is therefore a critical parameter in the water balance and transmission loss calculations. This study shows that it is possible to constrain the water balance using hydrodynamic models in dryland river systems using remote sensing and simple field measurements to address the otherwise scarce availability of data. The results of this study also enable a better understanding of the water resources available for ecosystems in these unique multi-channel and large floodplain rivers. The combined modelling/remote sensing approach of this study can be applied elsewhere in the world to better understand the water balances and water transmission losses, important drivers of ecohydrological processes in dryland environments.

1. Introduction

Drylands cover approximately one-third of the Earth's surface and their limited water resources are under increasing pressure (Williams, 1999). Dryland regions are characterised by highly variable rainfall and episodic river flows (Tooth, 2000), often resulting in rivers with a unique geomorphological form—ana branching—which is characterised by low-gradient and multi-channel river systems with large floodplains that are graded to transmit large yet infrequent and slow-moving flood pulses. Anabranching rivers with sizeable floodplain are found in dryland regions across the world, including South America (Smith, 1986), China (Wang et al., 2005), Australia (Knighton and Nanson, 2001; Nanson et al., 1986; Schumm et al., 1996), North America

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(Schumann, 1989; Smith, 2009; Smith and Smith, 1980), Africa (Makaske, 2001) and Europe (Gurnell et al., 2009).

The wide floodplains of many of these rivers are often only inundated during major flood events at sub-decadal to multi-decadal frequencies (Costelloe et al., 2006; Jarihani et al., 2013; Kingsford et al., 1999; Knighton and Nanson, 1994). These large yet infrequent flood events fill enlarged channel segments (or waterholes), recharge aquifers (Cendón et al., 2010) and support the flora and fauna of these systems, which are often adapted to 'boom-and-bust' ecological cycles (Costelloe et al., 2006; Kingsford et al., 1999; Puckridge et al., 2000). These flood pulses are also known to have large transmission losses which result in diminishing discharge downstream and therefore exert considerable control on the water resource availability that is important to the ecohydrology of such systems (Knighton and Nanson, 1994).

The large transmission losses are broadly related to the majority of rainfall falling in the headwaters generating a relatively slow moving flood pulse travelling through a low-gradient and dry landscape with highly variable infiltration capacity and significant evaporative demands. Transmission losses are then a combination of actual evaporation (here direct evaporation from the flood water surface), infiltration to soils and groundwater and terminal water storage in waterholes and local floodplain depressions. Because of: (i) the remoteness of dryland rivers; (ii) their episodic flow regime; and (iii) low levels of economic development, there is often a lack of water gauging infrastructure (often gauges are tens-to-hundreds of kilometres apart, Costelloe et al., 2003) with which to directly estimate transmission losses. This restricts our ability to accurately understand flood dynamics, the partitioning of total transmission losses into its separate components, and ecohydrological processes of such systems.

While dryland anabranching river systems are known to have some of the highest spatial and temporal variability in streamflow worldwide (Puckridge et al., 1998), how losses are partitioned as flow is transmitted downstream remains a key knowledge gap (Costelloe et al., 2003; Knighton and Nanson, 1994). Conventional modelling approaches to estimate transmission loss partitioning are also limited by the lack of adequate water gauging and climate observations. From the sparse gauging network in the 'Channel Country' rivers of the Lake Eyre Basin, Australia, current transmission loss estimates range between 70% and 98%) within ~350 km of the mid to lower catchment reaches (Costelloe et al., 2003; Knighton and Nanson, 1994; Thomas, 2011), and most years 100% of the flow is eventually lost in the lowest reaches of the catchment, or else enters the terminal Lake Eyre.

Estimating total transmission losses and/or individual components in dryland river systems has previously been undertaken using three main approaches (Cataldo et al., 2004, 2010): (i) small-scale field experiments (Dahan et al., 2008; Dunkerley and Brown, 1999; Dunkerley, 2008; Maurer, 2002; Parsons et al., 1999); (ii) interpolation of sparse streamflow networks using simple regression and/or differential equations (Arnott et al., 2009; Costelloe et al., 2006; Knighton and Nanson, 1994, 2001; McCallum et al., 2012; Schmadel et al., 2010); and (iii) water balance modelling to allow estimation of total and component transmission losses (Morin et al., 2009). Key papers for these approaches are summarised in Table 1, and includes examples where hydrodynamic modelling has incorporated remotely sensed data in order to: (i) provide input data; (ii) calibrate and validate such models; and (iii) estimate various components of transmission losses (Karim et al., 2011; Milewski et al., 2009; Sharma and Murthy, 1994).

In data-sparse dryland regions, remote sensing data have been used to provide:

(i) basic topographic forcing data (Callow et al., 2007; DeVogel et al., 2004; Hancock et al., 2006; Hirt et al., 2010; Jarihani et al., 2015; Leon and Cohen, 2012; Rexer and Hirt, 2014);
(ii) hydrometeorological data (Khan et al., 2012, 2011; Milewski et al., 2009; Xue et al., 2013; Yao et al., 2014);
(iii) flood inundation maps (Brivio et al., 2002; Cruz et al., 2010; Frazier and Page, 2000; Jarihani et al., 2014; Schumann et al., 2007; Sheng et al., 2001);
(iv) quantification of flood levels (Baghdadi et al., 2011; Birkett and Beckley, 2010; Jarihani et al., 2013; Troitskaya et al., 2012; Zhang et al., 2011);
(v) discharge estimation (Callow and Boggs, 2013; Frappart et al., 2005; Kouraev et al., 2004; Smith et al., 1996; Zhang et al., 2004);
(vi) evapotranspiration estimation (Donohue et al., 2010; Glenn et al., 2011; Mohamed et al., 2004; Smettem et al., 2013; Zhang et al., 2009);
(vii) infiltration estimation (Frappart et al., 2008); and
(viii) estimation of terminal water storage (Frappart et al., 2005).

This demonstrates the potential for remote sensing to constrain individual components of hydrological processes is extremely high and now well recognised. However, the ability to integrate many of these individual components in order to parameterise, calibrate and validate hydrodynamic models in data-sparse dryland river systems for the investigation of the water balance dynamics is not well established.

To better understand the partitioning of transmission losses in dryland flood events, we used a novel combination of minimal field data, remote sensing, and hydrodynamic modelling. By using this modelling approach, we can advance our understanding of floods in these dryland landscapes and their implications for the water balance and ecology, and improve the status of modelling of remote and data-sparse hydrological systems. This paper has three objectives:

(1) to build a hydrodynamic model using remotely-sensed inputs to augment traditional hydrological data for a series of linked reaches along a dryland anabranching river system;
(2) to use a hydrodynamic model to investigate the water balance and associated uncertainties, and to establish the partitioning of transmission losses (actual evaporation, infiltration to the soil moisture store and terminal water storage); and
(3) to evaluate the opportunities, limitations, potential and future directions of using remotely-sensed data to better understand water balance and hydrodynamics of dryland and data-sparse regions.

2. Study site

The Diamantina River above the Diamantina Lakes gauging station (catchment area = 55,721 km^2) was selected for this study (Fig. 1). The Diamantina River is a major tributary of Lake Eyre Basin (LEB), one of the world largest endorheic basins (spreading over 1.14 million km^2), of arid central Australia. The Diamantina river rises in Swords Range and flows north-east before turning clockwise and flowing southwest where it is joined by two major tributaries (Mayne and Western Rivers) above the Diamantina Lakes gauging station (Fig. 1).

The river has a very low-gradient with a large anastomosing channel system which features up to hundreds of individual channels spread across a floodplain that can inundate to a width of up to 60 km (Bullard et al., 2007; Costelloe et al., 2003; Jarihani et al., 2015; Knighton and Nanson, 2001). Floods normally develop in the headwaters of the catchment and are more frequent during La Niña