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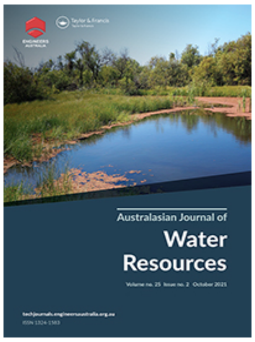

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RESEARCH ARTICLE

Dynamics and scales of transmission losses in dryland river systems: a meta-analysis

Never Mujere [a], Mhosisi Masocha [a], Hodson Makurira [b] and Dominic Mazvimavi [c]

[a]Department of Geography and Environmental Science, University of Zimbabwe, Harare, Zimbabwe; [b]Department of Civil Engineering, University of Zimbabwe, Harare, Zimbabwe; [c]Department of Earth Sciences, University of the Western Cape, Cape Town, South Africa

ABSTRACT
In this paper, 245 studies were reviewed to understand approaches used for estimating river channel transmission losses. Findings indicate that regression equations, differential equations, flow routing, experimental approaches and water balances are most widely used. Geographic Information Systems are becoming a convenient framework to display model results showing spatial variability of losses. In the United States, regression equations and experimental approaches involving controlled releases are widely used to assess transmission losses whereas in the dryland regions of Australia, water balance and flow routing approaches are popular. In Africa and Asia, regression equations and water balances are common approaches to estimate transmission losses. By using regression equations on data pooled from studies done in different dryland regions of the world, statistically significant ($p<0.05$) relationships were observed between transmission loss volume and, reach length, inflow, flow contributing area and runoff coefficient. Overall, the review underscores the importance of channel and catchment characteristics in shaping the dynamics of transmission losses. Two main limitations of the current approaches are that they are site-specific and require high amounts of data not always available in dryland regions due to sparse network of monitoring stations. The review also highlights existing knowledge gaps and future research needs.

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Drylands; meta-analysis; river channel transmission losses; regression equations; differential equations; flow routing; field experiments; water balance; spatial models

1. Introduction

1.1. Background and environmental context

River reaches experience flow losses downstream unless they are augmented by tributary inflows, baseflow, groundwater inflow and channel precipitation (Walters 1990; Choi 2016). These losses, known as transmission losses occur in any climate and are best characterised relative to the river reach since they vary as the reach scale changes. From a water management perspective, it is important to understand the variations in transmission losses otherwise downstream users may be charged for water they have not received. In drylands (that is, arid and semi-arid regions) accurate information on the magnitude and patterns of transmission losses is critical for sustainable management of water owing to extremely variable flow regimes. These regions cover approximately one-third of the Earth’s surface, receive annual precipitation of 100 mm-800 mm and sustain almost 40% of the world’s population (Jarihani et al. 2015).

The need for special attention to transmission losses occurring within dryland regions is justified because of unique environmental settings that have the potential to amplify the losses. For instance, high actual evapotranspiration from open water surfaces and riparian vegetation, large variability in rainfall inputs and high atmospheric moisture demand trigger considerable variation in runoff generation. The variable antecedent soil moisture and vegetation cover have significant impacts on infiltration processes (Lane, Diskin, and Renard 1971; Lane 1985; Gu and Deutschman 2001; Thomas, Stewart, and Constantz 2000; Greenbaum et al. 2002). It therefore becomes critical to discuss transmission losses in these regions for accurate assessment of available surface water resources, prediction of peak discharges as well as to estimate groundwater recharge from river channels and floodplains (Walters 1990; Din, Dousari, and Ghadban 2007; Shaw and Cooper 2008; Wu, Zhen, and Lin 2011; Shanafield and Cook 2014).

Studies in drylands have shown that river channel transmission losses are significant in supporting riparian vegetation and channel associated ecosystems (Costa, Bronstert, and De Araujo 2011), reducing flood or peak discharges (Dunkerley and Brown 1999; Lange 2005), estimating design floods, freshwater supply and improving water quality (Gippel 2006; Ball et al. 2016). For example, transmission losses were integrated in updating the Australian Rainfall Runoff project guidelines (Ball et al. 2019). In addition, knowledge of transmission losses was found to be valuable in flood design to address climate

CONTACT Never Mujere nemuj@yahoo.co.uk

change risks (Ball et al. 2016) and in quantifying volumes of water available for diversion in the Coorong South Lagoon (Montazeri et al. 2011) as well as improving the management of Murray River storages (Gippel 2006; Murray-Darling Basin Authority 2019).

Research has shown that both allogenic rivers whose sources are in upstream humid areas such as the Nile River and, endogenic rivers whose sources are within the dryland environments such as Cooper Creek and Diamantina River in central Australia, experience channel transmission losses (Knighton and Nanson 1994; Mohammadi, Ryu, and Costelloe 2013; Saber et al. 2013). The processes accounting for transmission losses along river reaches have also received adequate attention in the literature. For instance, infiltration is the main cause of loss in alluvial channel banks and river beds underlain by fractured rocks (Bren 2005; Fu and Burgher 2015). Nevertheless, infiltration losses are critical sources of groundwater recharge to underlying alluvial aquifers which are major sources of water in drylands (Dahan et al. 2008; Costa, Bronstert, and De Araujo 2011), and provide soil moisture to riparian vegetation (Sophocleous 2002).

Evaporation from free water surfaces accounts for high percentage of losses in rivers with wide and shallow reaches such as the Limpopo River in southern Africa (Hughes 2009). On the other hand, transpiration by riparian and aquatic vegetation is a dominant contributing factor to transmission losses in vegetated channel reaches (Sophocleous 2002), whereas terminal storage or ponding in channel pools and overbank flows account for most transmission losses in floodplains (Lange 2005; Schoener 2017).

While the processes accounting for river channel transmission losses are well known, untangling the multiple drivers of transmission losses and their appropriate fluxes using a coherent conceptual framework remains a considerable research challenge. Hence, the objective of this paper is to develop a coherent framework for river channel transmission losses. In this paper, the processes influencing the loss rates such as infiltration, evaporation, transpiration, diversion and terminal water storage, are examined. The state of science in the estimation of transmission losses and, the strengths and limitations of the approaches available are highlighted. A discussion on how the approaches of estimating transmission losses vary in space and time is undertaken. Finally, a meta-analysis of published transmission loss data to examine relationships between river channel transmission losses and, reach length, flow entering the reach, runoff contributing area and runoff coefficient (that is, the ratio of the amount of runoff generated to amount rainfall received in an area) is conducted.

1.2. Conceptual framework

River reaches are characterised based on their interaction with groundwater in all types of landscapes. Losing river reaches recharge groundwater whereas gaining river reaches discharge water from underground sources through baseflow (Cataldo et al. 2004, 2010).The pattern of ephemeral and intermittent flow regimes is influenced by a wide range of meteorological inputs and basin processes. These are critical in determining the antecedent soil moisture conditions and can be integrated into a simple framework (Figure 1).

The framework shown in Figure 1 can be represented means of an equation which incorporates transmission loss processes of: (1) infiltration *(I)* into the river bed, banks, bars and the floodplains, (2) evaporation *(E)* from water and soil surface, (3) transpiration (T_r) from riparian vegetation, (4) terminal or temporary surface water storage (T_{WS}) that is, ponding in channel depressions and/or floodplains, (5) flow into distributaries or effluent channels $(Q_d$*and* (and (5) channel diverted flow (Q_{dv})(Shentsis et al. 1999):

$$T = I + E + T_r + T_{ws} + Q_d + Q_{div} \tag{1}$$

This framework can be applied to address the challenges of measuring and modelling transmission losses in dryland regions by zooming in on the processes involved (Hughes 2009; Lang et al. 2015). Estimating the total or the sum of individual components remains a considerable modelling challenge due to scarcity of measurement infrastructure and difficulty in accurately accounting for the flow distribution in large multi-channel floodplain systems. High uncertainties of parameters constrain model accuracy (Knighton and Nanson 1994; Tooth 2000; Knighton and Nanson 2001; Tooth and Nanson 2011; Tooth 2013).

With regard to infiltration, although this process is complex for it depends upon the gradient of total soil water potential at the ground surface (Lange 2005; Schreiner-McGraw, Ajami, and Vivoni 2019), it is highly sensitive to soil moisture antecedent conditions. The dryland landscape setting drives considerable variation of infiltration losses in both space and time. Infiltration is high in floodplains with sandy or loam soils, high total head to drive infiltration, large surface areas to lose water and alluvial channels that have long total residence duration of water (Bren 2005; Fu and Burgher 2015).

Studies of small to medium-sized catchments with low to moderate relief gradients done in Arizona (Walters 1990), in India (Sharma and Murthy 1995), in South Africa (Hughes and Sami 1992) and in Namibia (Dahan et al. 2008) have identified infiltration losses to the near-surface channel aquifer as a major component of transmission loss dominating headwaters and mid-reaches of rivers. In

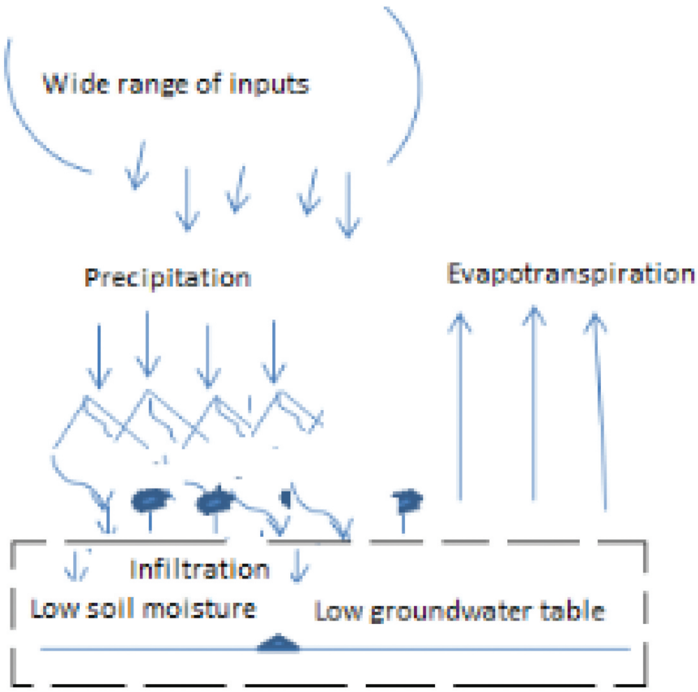

Figure 1. Conceptual model showing transmission loss components.

quantitative terms, almost 75% of the total flow volume was recorded as infiltration into the channel bed during the first flow event after a long dry period in a semi-arid watershed in South Africa. During the second flow event after 42 days of no flow, infiltration losses decreased to 22% of the total volume (Hughes and Sami 1992). Infiltration rates are particularly high during the initial or first flow events after a long dry period in sand beds and if there are cracking clays with large fissures. With time, infiltration gradually decreases with wetting towards a steady final rate due to formation of a clogging layer and sediment cohesion (Thomas, Stewart, and Constantz 2000). At the same time, there may be increased resistance to seepage of water at the soil surface due to surface sealing as a result of swelling of clay, water breaking down soil aggregates and subsequent inwash of finer soil particles (Knighton and Nanson 1994; Costelloe et al. 2003; McMahon et al. 2008).

In dryland river systems, evaporation is as significant component of channel transmission losses.For example, studies have shown evaporation account for 16–20% of the transmission losses along the 80 km reach of Colorado River (Daesslé et al. 2016). The rates of evaporation from intercepted rainfall, open water surfaces, wetted channel and floodplain soils are generally high given the large atmospheric moisture deficit driven by a combination of high energy supply and limited advection of moisture (McMahon et al. 2008, 2013). In some systems evaporation is enhanced during times of high discharge by the large surface area and relative shallowness of floodplain flows. The proportion of available water that is lost through evaporation in dryland river systems is seasonally variable due to variations of flow duration and amount, and hydraulic conductivities of alluvial deposits flooring river valleys (Boroto and Görgens 2003). It is also seasonally variable because within the tropics there is seasonal variation in solar radiation which provides much of the energy that drives evaporation. Nevertheless, the estimation of direct evaporation from moving water is still a research challenge.

The proportion of available water that is lost through transpiration varies due to the amount of vegetation cover present under arid and semi-arid conditions (Boroto and Görgens 2003). Studies along the Diamantina River have indicated that transpiration losses can be as high as 21.6% (Jarihani et al. 2015) and as low as 2–8% (Thomas, Stewart, and Constantz 2000).Also, transpiration losses along the Limpopo River were shown to vary from 5% to 15% (Boroto and Görgens 2003). High vegetation cover increases rates of transpiration whereas low transpiration rates result from sparse or absence of vegetation cover. Riparian vegetation along river corridors take advantage of high moisture availability and thus increases transpiration (Knighton and Nanson 1994; McMahon et al. 2008).

Terminal water storage in pools, subsidiary channels, floodplains and artificial embankments along enlarged channel segments can persist for long durations and become an important transmission loss component. However, as pools become fully saturated and channel fully active during floods, the rate at which flow is transmitted downstream along the channel or river transmission efficiency increases (Knighton and Nanson 1994). This reduces transmission losses as most of the flow moves downstream. Overbank flows ponded in floodplain depressions can reconnect with main channel, albeit at a slower rate than channel flow due to friction with riparian vegetation. Studies show that terminal storage accounted for 11.2% of the transmission losses along the 180 km reach of the Diamantina River (Jarihani et al. 2015).

Distributaries are effluent channels that divert flow from main river channel into floodplains. Flow entering into distributaries never reconnects with main channel downstream, thus increasing river flow transmission loss. (Knighton and Nanson 1994; Lange 2005).In many rivers in Australia, water is lost to distributary channels, for example, the Avoca River has two large distributary channels that end in terminal lakes.

Artificial diversion of surface water from rivers particularly for consumptive use and irrigated agriculture alters river streamflow regimes by reducing baseflows, overbank flooding, magnitude and frequency of flow pulses and, attenuation or complete reversal of the natural seasonal flow pattern (Stewardson and Guarino 2018). Studies have shown that flow diversion in the Murray River basin via pumps and weirs into irrigation channels accounted for 87% of the losses (Murray-Darling Basin Authority 2019) and along the Limpopo River flows diverted for irrigation reduced reach inflows by 14% (Boroto and Görgens 2003). For this study, selected river reaches were unregulated.

2. Methods

2.1. Literature search

In this study, a search strategy comprising Boolean logic, wildcards and truncation was used to locate relevant scientific literature on approaches for estimating river channel transmission loss. Specifically, the search targeted 'river*' OR 'stream*' OR 'channel*' AND 'transmission loss*' OR 'model*' OR 'method*' OR 'technique*' OR 'approach*' used in the title, abstract, keywords and references. A two-tier screening approach was then used to assess the appropriateness of the studies retrieved by the search strategy. First, titles, abstracts, and keywords of publications available in English were reviewed. The retrieved publications were then further examined to select those focusing on modelling transmission losses as their core subject matter. Then, the strengths or limitations and practical applications of specific modelling approaches were evaluated. To be considered relevant, selected studies had to be conducted in unregulated river systems where no large infrastructure control river discharge in at least part of the study area.The results from reviewed papers were assumed reliable because they had undergone peer review. Nevertheless, the limitation of this approach is that some relevant articles besides those written English were not included. This review can also be susceptible to publication bias, where data from statistically significant studies are more likely to be published than those from studies that are not significant (Drucker, Fleming, and Chan 2016). In such cases, the literature review becomes biased towards articles reporting significant results.

2.2. Distribution of sites where transmission losses were investigated

To map distribution of sites where transmission loss studies were conducted, coordinates were needed. Some studies reported the coordinates of the sites whereas other studies did not specify the coordinates. Instead they used place names to georeference the study site. The place names were searched on Google Earth and coordinates of the identified names were obtained. To extract coordinates of a site such as Walnut Gulch experimental station in Arizona reported as a place, Google Earth was used to search the place name and obtain the coordinates. A limitation of this approach is that the coordinates were not precise but gave a general location of where the studies were conducted. The points were overlaid on a world base map showing country boundaries downloaded from Diva GIS. A point map showing the distribution of study sites of transmission losses was created in a GIS.

2.3. Meta-analysis

To establish relationships between transmission loss and channel characteristics as well as runoff, studies that reported data on inflow, outflow, reach length, rainfall and flow contributing area that is, catchment area between the upstream and downstream gauges of the reach were first identified. Then the data on these variables were extracted, pooled and regressed against transmission loss using linear regression models. Where transmission loss values were not reported in the original studies, the difference between reach inflow and outflow volumes was calculated. As the magnitude of losses. The number of studies that reported on these predictors of transmission loss ranged from 15 for transmission loss versus flow contributing area and runoff coefficient to 50 for transmission loss versus reach length and reach inflows.

Prior to performing regression, the data were first checked for normality using Kolmogorov-Smirnov (K-S) test. For data which deviated from normality ($p < 0.05$), a log-transformation was performed to make them normal. No transformations were performed for data pertaining to the relationships between river transmission loss and, flow contributing area and runoff coefficient obtained from 15 studies because the data sets were normally distributed (contributing area; p = 0.610; runoff coefficient, p = 0.906; transmission loss, p = 0.159). To derive the relationship between runoff coefficient and transmission loss, the amount of rainfall received in the flow contributing area and runoff generated were used to estimate event-based runoff coefficient. Runoff coefficient was derived as the ratio of channel reach outflow to rainfall received in the flow contributing area. The flow contributing area is the drainage area between river reach inflow and outflow gauging stations.

Data for the relationship between transmission loss and, reach length and reach inflow reported in 50 studies were not normally distributed as their p-values were less than 0.05 when tested using the Kolmogorov-Smirnov (K-S) normality test (reach length: p = 0.001; reach inflow, p = 0.002; transmission loss: p = 0.005). After the data were log-transformed they followed normal distribution (reach length: p = 0.963; reach inflow, p = 0.345; transmission loss, p = 0.857).

The nature and statistical significance of the relationships between transmission losses and the four explanatory variables were evaluated using the coefficient of determination, R^2 and p-values respectively. Alpha, $\alpha = 0.05$ was taken as the critical level of significance.Where the p-value was less than or equal to the significance level, sample data provided sufficient evidence to conclude that the regression model fitted data better than the model with no independent variables. Thus, the decision was to reject the null hypothesis and conclude that the result occurred by chance not due to sampling errors.

3. Results

3.1. Approaches for estimating transmission losses

In this review, six approaches applied in estimating transmission losses were identified; namely simple regression equations, differential equations, experimental, flow routing, water balance and model-based approaches implemented in GIS (El-Hames and Richards 1998; Hacker 2005; Rivaz and Musavi-Jahromi 2012; Ibrahim et al. 2017; Pacheco-Guerrero et al. 2017). Table 1 shows the model structure, underlying assumptions and limitations of the six approaches for estimating transmission losses. It can be observed that discharge, reach length, hydraulic conductivity and channel storage are the main variables used to estimate transmission loss. The experimental approach which calculates transmission loss as the difference between reach inflow and outflow is the simplest to use but requires a field campaign and monitoring equipment. Flow routing approaches stand out in that they explicitly incorporate the combined effects of time, flow rate and channel storage. In more recent studies, transmission loss is being estimated as a product of hydraulic conductivity of the channel bed, flow travel time, channel perimeter and reach length in a GIS. For instance, Mohammadi, Ryu, and Costelloe (2013) and Pacheco-Guerrero et al. (2017) used this modelling framework and GIS software to display spatial variability of transmission loss.

Simple regression equations use data for river reach inflow and outflow from a number of events and river reaches to estimate transmission losses.Relationships between transmission losses and other independent variables such as inflow can be developed (Sorman and Abdulrazzak 1993; Schwartz, Schick, and Enzel 2002). The strength of this approach is that it is straight forward to implement. However, regression equations lack direct connection to the specific physical processes governing transmission losses. Accordingly, variability in losses at sites not in the dataset cannot be determined (Walters 1990; Sharma and Murthy 1994).

Simplified differential equations conceptualise an ephemeral river channel as a reservoir capable of representing transmission loss based on relationships between storage and discharge. The equation shows infiltration loss as function of discharge and time, and high loss at the onset followed by decrease to nearly constant. The strength of this approach is that it shows temporal variations of losses. However, the weakness of the approach is that it represents transmission losses from single events only.

Experimental approaches are conducted at specific locations of river reaches using controlled water releases (Babcock and Cushing 1942; Sharp and Saxton 1962; Li et al. 2011; Saber et al. 2013; Huang et al. 2015; Schoener 2017). The strength of this approach is that different components of transmission losses can be accurately estimated. However, experimental studies require large amounts of resources and cannot be conducted in inaccessible areas.

Flow routing approaches applied to predict the variations of flow as it moves through a river reach by solving partial differential equations relating, for example, storage within the reach and discharge at the outlet (El-Hames and Richards 1998; Morin et al. 2009; Ghobadian and Khalaj 2015). Strengths of the routing approaches lie on their ability to show temporal variations of flow along river reaches. However, they can only estimate losses over short river reaches correctly (Knighton and Nanson 1994).

With regards to the water balance approach, transmission loss is estimated as the difference between reach input flow at the upstream gauging station and

Table 1. Appraisal of river channel transmission loss approaches.

Approach	Description and equation	Assumptions	Limitations	References
1. Regression equations	A series of measurements of river reach inflow and outflow volumes are used to establish simple linear relationship between reach inflow volume and transmission loss volume. $T = bQ_i + a$ where: T is the volume of transmission losses in the reach (m^3), Q_i is the reach inflow volume (m^3), a is the intercept and b is the slope of the best fit regression line, a and b are related to hydraulic conductivity, mean volume of flow to the reach and the mean duration of flow in the channel reach.	1. Volume of transmission loss in a reach is proportional to volume of reach inflow. 2. Rate of transmission loss along channel reach is constant (i.e. a steady-state loss rate). 3. Rate of lateral tributary inflow is zero long the channel reach length during flow events.	1. Lack a direct connection to the specific physical processes governing transmission losses. 2. Require long term data monitoring to establish the statistical relationship. 3. Are less general in application.	Lane, Diskin, and Renard (1971), Lane, Ferreira, and Shirley (1980), Sorman and Abdulrazzak (1993), Sharma and Murthy (1995), Gu and Deutschman (2001), Boroto and Görgens (2003), Cataldo et al. (2004), Hacker (2005), Reid and Frostick (2011), Pacheco-Guerrero et al. (2017).
2. Differential equations	Simplified differential equations are used to model changes in reach inflow with respect to reach $_i$length. $\frac{dQ_i}{dx} = -kQ_i$ where: Q_i is the reach inflow volume (m^3), x is the channel reach length (m) and k are empirical parameters with values related to effective steady-state hydraulic conductivity, mean duration of inflow to the reach, and mean volume of inflow to the reach *Qi*.	1. Uniform infiltration, and channel properties e.g shape and width over a river reach. 2. Volume of loss in a channel reach is proportional to the volume of upstream flow. 3. The loss rate along channel reach is constant 4. Rate of lateral tributary inflow is zero along the channel length during the flow event.	1. Limited applicability when used as the sole model for estimating transmission losses. 2. Represent transmission losses from single events only.	Lane (1985), Sharma and Murthy (1994; 1995), Rao and Maurer (1996), Ghobadian and Khalaj (2015), Blythe and Schmidt (2018).
3. Experimental	A well-structured system of measurements is set up in experimental watersheds to perform small-scale controlled field experiments relying on direct observations during flow events at specific locations. Experimental data form the basis of other approaches. $T = Q_i - Q_o$ where: T is the transmission loss (m^3), $Q_i$is channel reach inflow (m^3) and Q_o is the channel reach outflow (m^3)	The controlled conditions do not significantly vary from natural settings.	1. Applicable to site-specific contexts hence limited applicability. 2. Expensive to conduct, need large data, lots of effort, special equipment and techniques. 3. Applicable for small scale or reach-based estimation of transmission losses.	Keppel and Renard (1962), Lane (1985); Reid, Laronne, and Powell (1998), Dahan et al. (2007); Dunkerley and Brown (1999), Huang et al. (2015), Schoener 2017), Blythe and Schmidt (2018).
4. Flow routing	This involves theoretical modelling founded on physical infiltration equations. The approach is used to predict the temporal and spatial variations of a flood as it moves through a river reach or reservoir. By examining changes in the shape and timing of the hydrograph at different points downstream the effects of storage and flow resistance within a river reach are explored. $\frac{dS}{dt} = Q_{ir} - Q_{or} = T_r$ where: *Tr* is the transmission loss rate (m^3/s), Q_{ir} is the reach inflow discharge (m^3/s), Q_{or} is the reach outflow discharge (m^3/s), S is the reach storage (m^3) and t is the time (s).	1.Prior knowledge of inflow conditions are known. 2. No significant backwater effects that raise water levels behind an obstruction in the channel. 3. Initially channels are dry.	1. This approach is time consuming, expensive, requires large amounts of data and needs a lot of effort. 2. Estimate a river's output hydrograph over short distances correctly. 3. The models require prior knowledge of the inflow conditions and can be applied for catchment scale analyses,	Knighton and Nanson (1994), Sharma and Murthy (1995), El-Hames and Richards (1998), Cataldo et al. (2004), Lange (2005), Morin et al. (2009), Ghobadian and Khalaj (2015), Lininger and Latrubesse (2016), Nguyen et al. (2018), Hughes (2019).

(*Continued*)

Table 1. (Continued).

Approach	Description and equation	Assumptions	Limitations	References
5. Water balance	Reach water balance parameters including inflow, outflow, lateral inflow and precipitation are estimated to obtain transmission losses.$T = Q_i + Q_l + P - Q_o$where: T is the transmission loss (m^3) along a channel reach, $Q_i$is the reach inflow at the upstream gauging site (m^3), $Q_l$is the lateral inflow (m^3), $Q_o$is the reach outflow at downstream gauging site (m^3) and P is the reach precipitation volume (m^3) .	Uncertainties on the parameters are addressed before modelling.	1. Verification require a lot of data 2. Difficult to account for transmission losses from high magnitude flood flows which bypass gauging sites. 3. Can be difficult to determine tributary runoff contribution.	Sharp and Saxton (1962), Lane (1985), Sorman and Abdulrazzak (1993), Abdulrazzak and Sorman (1994), Osterkamp, Lane, and Menges (1995), Shentsis et al. (1999), Schwartz, Schick, and Enzel (2002), Walters (1990), Ibrahim et al. (2017), Schreiner-McGraw, Ajami, and Vivoni (2019).
6. GIS based models	Other approaches using spatial data are implemented in a GIS environment to estimate transmission losses.$T = KPLt$where: T is the transmission loss (m^3), K is the hydraulic conductivity (m/s), t is the travel time (s), P is the wetted perimeter of the channel (m) and L is the length of the channel (m).	No repeated incision along the river reach because it changes channel configuration.	1. Requires lots of data on the river reach characteristics (e.g. soil, channel morphology, flow characteristics) 2. Require long computational time and time to develop input data sets.	Hacker (2005), Rivaz and Musavi-Jahromi (2012), Mohammadi, Ryu, and Costelloe (2013), Pacheco-Guerrero et al. (2017). Hughes (2019).

Table 2. Characteristics of approaches used for estimating transmission losses.

Criterion	Regression equations	Differential equations	Flow routing	Water balance	Experimental	GIS based models
Form	Statistical	Physical	Physical	Physical	Physical	Physical
Structure	Empirical	Empirical	Process based/ empirical	Process based/ empirical	Empirical	Process based
Data requirements	Low	Low	Moderate	High data driven	High data driven	Very high data driven
Level of complexity	Low	Low	Moderate	Moderate	High	High
Spatial scale	Reach	Reach	Reach/ basin	Reach/basin	Point/ reach	Pixel/ basin
Time dependence	Static	Dynamic	Dynamic	Dynamic	Dynamic	Dynamic
Applicability	Results not transferable Less accurate and reliable results	Results not transferable, Less accurate and reliable results	Parameters vary spatially and temporally within the basin	Site specific, provides estimates over a range of spatial scales	Difficult to conduct in inaccessible areas or sites. Results not transferable outside study sites	Parameters vary in space and over time. Reliable results, expensive

reach outflow at the downstream gauging station (Table 1). Upstream flow comprises channel precipitation along the reach, reach inflow at upstream gauge and lateral or tributary inflow. The strength of the approach is that the time-scale analyses can be varied such as event-based, monthly or annual averages (Osterkamp, Lane, and Menges 1995; Goodrlch et al. 2004). In addition, various components of transmission loss can be estimated. Nevertheless, the approach is limited by scarcity and poor quality of data to estimate water balance parameters in dryland regions.

Models based in a GIS are mathematical equations such as routing equations whose spatial variables are imported, analysed and output displayed in form of a map a GIS. The strength of the approach is that the output shows spatial variations of transmission loss at pixel scale (Nguyen et al. 2018). However, the approach is time consuming, and requires large amounts of data.

The information presented in Table 2 shows that data requirements are low for regression equations and differential equations whereas flow routing approaches require moderate amounts of data. On the other hand, the water balance, experimental and models implemented in a GIS all have high to very high data requirements. The spatial scale of measurement ranges from reach to basin for regression and models implemented in a GIS. In terms of applicability, the models implemented in a GIS allow parameters to vary in space and over time hence the results tend to be reliable. By contrast, the other five approaches rely on parameters estimated from the data hence cannot be applied in areas outside the study sites.

3.2. Distribution of sites where transmission loss studies were conducted

Figure 2 shows the 44 sites where the six approaches were applied to estimate river channel transmission losses. Nineteen (43.2%) of the study sites were located in midwest and western USA where experimental watersheds such as the Walnut Gulch were set up to conduct controlled runoff studies. Africa and Asia had a similar number of 8 (18.2%) sites each, where transmission loss studies were conducted. In Europe, the studies were conducted in 5 sites (11.4%) whereas Australia had only 4(9.1%) of the sites.

Table 3 shows distribution of approaches used in estimating river channel transmission loss as reported from the five continents. In the United States most (73%) transmission loss studies were conducted followed by Australia with 13% of the reviewed studies. The United States had the highest number of studies using experimental approaches (94%), regression equations (50%) and differential equations (56%). Australia had the highest number of reported studies using water balance (42%) and flow routing approaches (50%) to estimate channel transmission losses.In tropical drylands of Africa, although 5% of the studies were conducted and only one study employed a model implemented in a GIS. Almost 3% of studies were conducted in Europe but none of the reported cases utilised regression equations and differential equations to estimate transmission losses.

Figure 3 shows the number of reported studies which applied the six approaches in determining river channel transmission losses. From the reported 245 studies, most studies (65%) applied experimental approaches to estimate transmission losses. Differential equations and flow routing approaches were each reported in 5% of the studies. Compared with other approaches, very few (4%) transmission loss studies had utilised models analysed in GIS during the review period.

3.3. Temporal patterns of applied approaches

Figure 4 shows trends of the reviewed six approaches as applied to estimate river channel transmission losses. Transmission losses were estimated from controlled

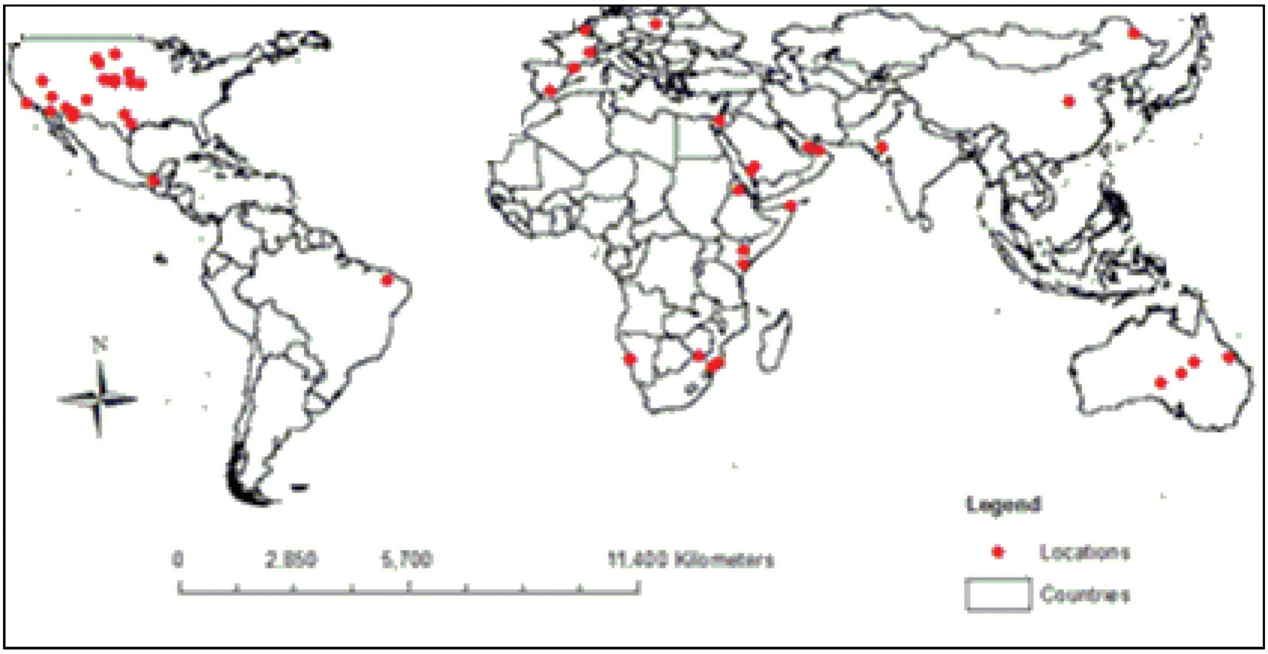

Figure 2. Location of sites where transmission loss studies using the six approaches were reported.

Table 3. Number of transmission loss studies conducted using the six approaches.

Place	Experimental	Regression equations	Water balance	Differential equations	Flow routing	GIS based models	Total
USA	150	13	4	9	2	2	**180**
Australia	5	5	10	2	6	2	**30**
Asia	1	5	5	1	1	2	**15**
Africa	2	3	3	2	2	1	**13**
Europe	1	0	2	0	2	2	**7**
Total							**245**

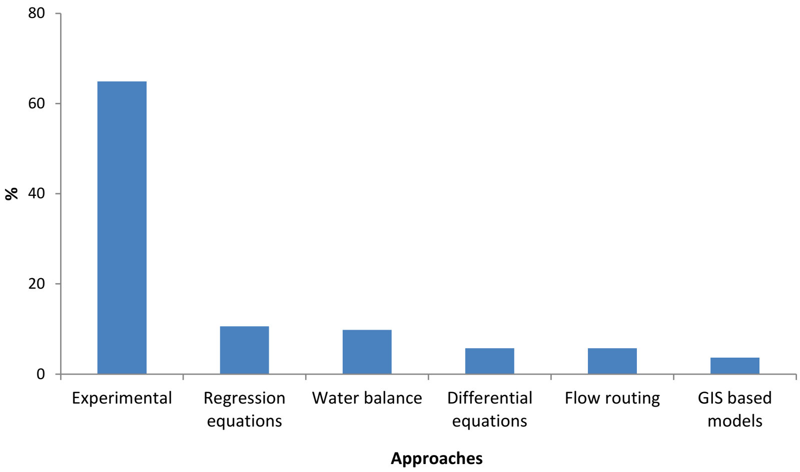

Figure 3. Number of studies utilising the six approaches to estimate transmission losses.

flow experiments conducted in experimental watersheds of the United States since 1918. From the late 1960s, regression equations and differential equations became popular approaches to estimate transmission losses. Between 1978 and 1989, water balance and flow routing techniques were introduced in estimating transmission losses. From the 1990s, the development of various GIS software allowed for spatial data obtained from other approaches to be handled, processed, analysed and displayed in a GIS. This allowed GIS based

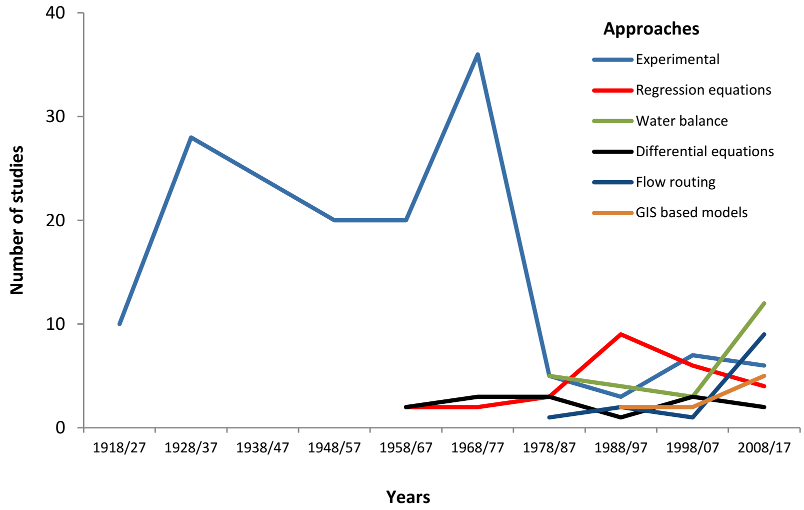

Figure 4. Temporal variation on applying transmission loss approaches.

modelling approaches to be applied in river channel transmission loss modelling. Water balance, flow routing and GIS based modelling approaches are increasingly used to estimate channel transmission losses.

3.4. Determinants of river channel transmission losses

Figure 5 shows the relationships between river channel transmission losses and (a) reach length, (b) reach inflow, (c) flow contributing area and (d) runoff coefficient. A strong and significant ($n = 15$, $R^2 = 0.795$, $F_{1,13} = 50.61$, $p = 0.000$) positive linear relationship was found between flow contributing area and transmission loss volume (Figure 5a). Variation in flow contributing area could explain almost 80% of the variation in transmission loss. Other factors not accounted for in the model could explain about 20% of the variation in transmission loss.

Figure 5(b) show a strong and significant ($n = 50$, $R^2 = 0.726$, $F_{1,48} = 127.31$, $p = 0.000$) positive linear relationship between reach inflow volume and transmission loss volume. Variation in river reach inflows could explain almost 73% of the variation in transmission loss volumes.

A moderately strong and significant ($n = 50$, $R^2 = 0.559$, $F_{1,49} = 60.93$, $p = 0.000$) positive linear relationship was observed between reach length and transmission loss volume (Figure 5c). Variation in reach length could explain almost 56% of the variation in river channel transmission loss.

Figure 5(d) shows a weak and significant ($n = 15$, $R^2 = 0.266$, $F_{1,13} = 4.710$, $p = 0.049$) linear relationship between runoff coefficient and transmission loss volume. The high degree of scatter in the data points suggest that there are other significant factors besides runoff coefficient strongly explaining variations of transmission loss.

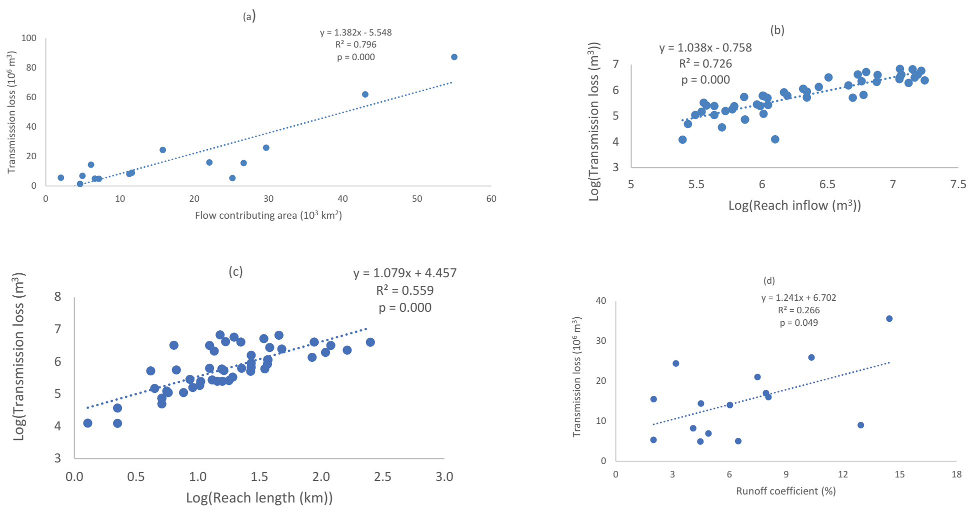

Figure 5. Significant relationships between river channel transmission losses and (a) flow contributing area, (b) reach inflow, (c) reach length and (d) runoff coefficient.

The statistically significantly ($p < 0.05$) relationships shown in Figure 5 imply that the regression models are a good fit of the data. Thus, flow contributing area, runoff coefficient, reach inflow and reach length could significantly predict transmission losses. Based on significant relationship between transmission loss (T) and flow contributing area (A) and runoff coefficient (Q) in Figure 5a and Figure 5d, the following statistically insignificant multiple linear regression equation was derived ($n = 15$, $R = 0.554$, $R^2 = 0.307$, $p = 0.111$, $F_{2,14} = 2.654$) as.

$$T = 4.382 + 0.116A + 0.578 \quad (2)$$

With regards to the relationship between transmission loss (T) and, reach inflow (I) and reach length (L) shown in Figure 5b and Figure 5c, a statistically significant multiple linear regression equation was also derived ($n = 50$, $R = 0.9$, $R^2 = 0.81$, $p = 0.000$, $F_{2,47} = 100.102$) as:

$$\log(T) = 0.298 + 0.768\log(I) + 0.52\log(L) \quad (3)$$

The multiple correlation coefficient (R) indicates that there is a strong and significant correlation between transmission loss and the two explaining variables. In addition, high value of the coefficient of determination (R^2) indicates that 81% of the variance of transmission loss is satisfactorily explained by the regression equation.

4. Discussion

4.1. Approaches used in estimating river channel transmission loss

The review has shown that approaches widely applied to estimate transmission losses vary from simple regression equations and differential equations to more complex physically distributed experimental, water balance, flow routing and models analysed in a GIS (Table 1). Studies have shown that combining regression and differential equations develop prediction equations which are more reliable than using them separately (Lane, Ferreira, and Shirley 1980; Lane 1985). Experimental approaches have long been used in estimating transmission losses since 1918 in the United States. The approaches, though expensive, are reliable. Recent approaches such as flow routing and GIS based modelling approaches show spatial variations of transmission losses. However, they are relatively sophisticated, require large volumes of data and high computer memory. Although these approaches are requiring lots of data, their output data are useful to calibrate or validate other modelling approaches.

4.2. Relationships between river channel transmission losses and the six explanatory variables

The meta-analysis showed a strong significant ($p = 0.000$) positive linear relationship between transmission loss volume and, flow contributing area and river reach inflow volume (Figure 5a). Variation in transmission loss could be explained by almost 80% of the variation in flow contributing area. This behaviour is similar to the one observed by Lange (2005) who showed that as the basin area increases, runoff generated also increases. Increase in flows resulted in enhanced water losses in flooded overbank areas. Also clogging layers in the streambeds are disrupted by high flows, thus enhancing infiltration. Nevertheless, runoff does not always increase with catchment area as shown by studies conducted in Africa and Australia. (McMahon et al. 1992).

A stronger significant ($p = 0.000$) positive linear relationship existed between reach inflow and river channel transmission loss (Figure 5b). In addition, 73% of the variation in transmission loss could be explained by the variation in reach inflow. Findings from this analysis are consistent with those by Lane, Ferreira, and Shirley 1980; Lane 1985; Lane, Ferreira, and Shirley 1980), Walters (1990), Sorman and Abdulrazzak (1993), Riddell et al. (2017) and Lange (2005) who also found significant linear relationships between transmission losses and reach inflow volumes. However, studies in south-east Saudi Arabia and Brazil have shown that channel transmission losses are related to reach inflow volume by power functions (Walters 1990; Costa, Bronstert, and De Araujo 2011).

The linear and power relationships between transmission losses and reach inflows indicate that transmission losses are high during peak flows and become low during small to medium flows due to enhanced water losses in flooded overbank areas. After a prolonged dry period, a clogging layer within or on the alluvial surface can act as a seal that is disrupted at high discharge to enhance seepage losses. In addition, enhanced bank storage processes by pools, diversions into subsidiary channels and floodplain areas act as sinks of flows at high discharges (Lange 2005; Riddell et al. 2017). High river levels increase hydraulic connection with wetlands and the area for seepage and evaporation. These processes increase losses (Murray-Darling Basin Authority 2019).

In contrast to increase in transmission losses with reach inflows, a study along the 180 km reach of Diamantina River in Australia show a negative linear relationship between transmission loss and flood discharge (Jarihani et al. 2015). Low peak flows resulted in large losses up to 68% while high peak flows were resulting in low losses down to 24%. It was observed that smaller flood events had a higher proportion of terminal water storage relative to total inflow as compared to larger flood events.

A moderate and significant (p = 0.000) linear relationship was observed between river channel transmission loss volume and reach length (Figure 5c). Variation in reach length failed to explain 46% of the variation in transmission loss. Similarly, studies have also observed increases in transmission losses from upstream reaches to downstream reaches due to increase in number of distributary channels, water residence time in the channel and/or floodplain, channel width and floodplain width (Dunkerley and Brown 1999; Jarihani et al. 2015). These factors increase actual evaporation, terminal storage and infiltration with distance downstream.

A weak and significant (p = 0.049) linear relationship existed between river channel transmission loss volume and, runoff coefficient (Figure 5d). Variation in runoff coefficient significantly explained 27% of the variation in channel transmission loss. Contrary to this observation, a non-linear and significant relationship between transmission loss and runoff coefficient was observed along a 420 km channel reach of the Cooper Creek River in Australia (Knighton and Nanson 1994). As runoff coefficient increases, transmission losses decrease and then increase after a certain threshold level of runoff coefficient is attained Small floods did not traverse the full distance between stream gauges, whereas larger flows transmitted to the outlet gauge about 20%–50% of their discharge. At a certain threshold level of input flow, transmission losses increased again due to enhanced overbank flows, and flows transmitted to the outlet were about 10%-20% of their discharge.

The moderate and significant relationships between transmission losses and, reach length can be attributed to complex nature of systems from which data were pooled. This is also true for the weak and significant relationship between transmission loss and runoff coefficient. Other explanatory variables could significantly explain variation of transmission better than runoff coefficient and reach length.

4.3. Research gaps

From the review, several knowledge gaps were identified. These include; the dynamics which influence the rate of loss, in addition to the areal extent which controls the total loss, the costs of getting transmission losses wrong in water resources management, uncertainties in current transmission loss approaches and the geomorphic importance of transmission losses. Compared to precipitation and streamflow, the magnitude of actual evaporation over the long term is difficult to estimate (McMahon et al. 2013). Current methods of estimating evaporation, which is a transmission loss component, are inadequate to couple full atmospheric mass balance. Semi-empirical and physical approaches such as Penman-Monteith and Priestly-Taylor models have inherent assumption of fixed water-air interface boundaries for open water bodies. There is little consideration for turbulence moving boundary, the effects of convection and advection of heat, which is an important driver of the water boundary condition and the moist air layer directly above. The key question then centres on approaches used to estimate fixed evaporation loss, which is an unaddressed issue in terms of measurement and theory for floodwaters. This is because almost all floodwater evaporation rates are derived from methods assuming standing (i.e. largely stationary) water bodies such as lakes, wetlands, and reservoirs, which derive estimates based on water body size or inundation area.

The issue of overbank flow is also a knowledge gap in dryland transmission losses given that the flow can reconnect with channels downstream, hence increases losses in the process. In some cases, (especially during floods) water that leaves the river channel flows to terminal storages or lakes and never returns to the main channel. This also complicates modelling of channel transmission losses. Lateral tributary inflow is a critical parameter in river reach water balance and transmission loss calculations, though often ignored or assumed negligible. These issues have not been tackled in previous transmission loss studies.

5. Conclusion

In arid and semi-arid regions, river channel flows usually decrease significantly in magnitude downstream because water is lost during seepage, evaporation, transpiration and ponding. These transmission losses are critical components of the hydrologic budget in arid and semi-arid regions, and should therefore, be included in hydrologic models that simulate rainfall-runoff processes. They are important not only in peak flow reduction, but also as sources of groundwater recharge to underlying alluvial aquifers.

River reach transmission loss is more commonly determined at the reach scale than watershed scale because the relevance of transmission losses is critical at small scales. The review has shown that losses can be estimated using regression equations, differential equations, flow routing, experiments, water balance and GIS-based model approaches. The strengths and weaknesses of the approaches differ depending on data requirements, resource needs and level of complexity.

The meta-analysis has shown significant relationships between transmission losses volume and, reach length, reach inflow, flow contributing area and runoff coefficient. Overall, this paper adds to existing database on river channel transmission losses.

Disclosure statement

No potential conflict of interest was reported by the author(s).

ORCID

Never Mujere http://orcid.org/0000-0001-6683-9560

References

Abdulrazzak, M.J., and A.U. Sorman. 1994. "Transmission Losses from Ephemeral Stream in Arid Region." *Journal of Irrigation and Drainage Engineering* 120 (3): 669–675. doi:10.1061/(ASCE)0733-9437(1994)120:3(669).

Babcock, H.M., and E.M. Cushing. 1942. "Recharge to Ground-water from Floods in a Typical Desert Wash, Pinal County, Arizona." *Eos, Transactions American Geophysical Union* 23 (1): 49–56. doi:10.1029/TR023i001p00049.

Ball, J., M. Babister, R. Nathan, W. Weeks, P.E. Weinmann, M. Retallick, and I. Testoni Editors) 2016. Australian Rainfall and Runoff: A Guide to Flood Estimation. Commonwealth of Australia (Geoscience Australia), Australia.

Ball, J., M. Babister, R. Nathan, W. Weeks, P.E. Weinmann, M. Retallick, and I. Testoni (Editors) 2019. "Australian Rainfall and Runoff: A Guide to Flood Estimation." Australia: Commonwealth of Australia(Geoscience Australia).

Blythe, T.L., and J.C. Schmidt. 2018. "Estimating the Natural Flow Regime of Rivers with Long-standing Development: The Northern Branch of the Rio Grande." *Water Resources Research* 54 (2): 1212–1236. doi:10.1002/2017WR021919.

Boroto, R.J., and A. Görgens. 2003. "Estimating Transmission Losses along the Limpopo River: An Overview of Alternative Methods." *International Association of Hydrological Sciences* 278: 138–143.

Bren, L.J. 2005. "The Changing Hydrology of the Barmah-Millewa Forests and Its Effect on Vegetation." *Proceedings-Royal Society of Victoria* 117 (1): 61.

Cataldo, J., C. Behr, F. Montalto, and R.J. Pierce. 2004. "A Summary of Published Reports of Transmission Losses in Ephemeral Streams in the US. A Report to the National Center for Housing and the Environment." Poolesville, MD: Wetland Science Applications; 42.

Cataldo, J.C., C. Behr, F.A. Montalto, and R.J. Pierce. 2010. "Prediction of Transmission Losses in Ephemeral Streams, Western U.S.A." *The Open Hydrology Journal* 4: 19–34. doi:10.2174/1874378101004010019.

Choi, W. 2016. "Streams, Gaining and Losing." *International Encyclopedia of Geography: People, the Earth, Environment and Technology* 1–4.

Costa, A., A. Bronstert, and J. De Araujo. 2011. "A Channel Transmission Losses Model for Different Dryland Rivers." *Hydrology and Earth System Sciences Discussions* 8: 8903–8962.

Costelloe, J.F., R.B. Grayson, R.M. Argent, and T. A. McMahon. 2003. "Modelling the Flow Regime of an Arid Zone Floodplain River, Diamantina River, Australia." *Environmental Modelling & Software* 18 (8): 693–703. doi:10.1016/S1364-8152(03)00071-9.

Daesslé, L., R. Van Geldern, A. Orozco-Durán, and J. Barth. 2016. "The 2014 Water Release into the Arid Colorado River Delta and Associated Water Losses by Evaporation." *Science of the Total Environment* 542: 586–590. doi:10.1016/j.scitotenv.2015.09.157.

Dahan, O., B Tatarsky, Y Enzel, C Kulls, M Seely, and G Benito. 2008. "Dynamics of Flood Water Infiltration and Ground Water Recharge in Hyperarid Desert." *Groundwater* 46 (3): 450–461. doi:10.1111/j.1745-6584.2007.00414.x.

Dahan, O., Y. Shani, Y. Enzel, Y. Yechieli, and A. Yakirevich. 2007. "Direct Measurements of Floodwater Infiltration into Shallow Alluvial Aquifers." *Journal of Hydrology* 344 (3–4): 157–170. doi:10.1016/j.jhydrol.2007.06.033.

Din, S.U., A.A. Dousari, and A.N.A. Ghadban. 2007. "Sustainable Fresh Water Resources Management in Northern Kuwait: A Remote Sensing View from Raudhatain Basin." *International Journal of Applied Earth Observation and Geoinformation* 9 (1): 21–31. doi:10.1016/j.jag.2006.03.001.

Drucker, A.M., P Fleming, and A.W Chan. 2016. "Research Techniques Made Simple: Assessing Risk of Bias in Systematic Reviews." *Journal of Investigative Dermatology* 136 (11): 109–114. doi:10.1016/j.jid.2016.08.021.

Dunkerley, D., and K. Brown. 1999. "Flow Behaviour, Suspended Sediment Transport and Transmission Losses in a Small (Sub-bank-full) Flow Event in an Australian Desert Stream." *Hydrological Processes* 13 (11): 1577–1588. doi:10.1002/(SICI)1099-1085-(19990815)13:11<1577::AID-HYP827>3.0.CO;2-L.

El-Hames, A., and K. Richards. 1998. "An Integrated, Physically Based Model for Arid Region Flash Flood Prediction Capable of Simulating Dynamic Transmission Loss." *Hydrological Processes* 12 (8): 1219–1232. doi:10.1002/(SICI)1099-1085(19980630)12:8<1219::AID-HYP613>3.0.CO;2-Q.

Fu, B., and I. Burgher. 2015. "Riparian Vegetation NDVI Dynamics and Its Relationship with Climate, Surface Water and Groundwater." *Journal of Arid Environments* 113: 59–68. doi:10.1016/j.jaridenv.2014.09.010.

Ghobadian, R., and M. Khalaj. 2015. "Incorporating Seepage Losses into a 1D Unsteady Model of Floods in an Ephemeral Stream." *Water SA* 41 (4): 464–471. doi:10.4314/wsa.v41i4.05.

Gippel, C. 2006. "Scoping Study of Operational Changes to Reduce River and Storage Losses along the River Murray System." Fluvial Systems Pty Ltd., Stockton, NSW. The Living Murray, Murray-Darling Basin Commission, Canberra.

Goodrlch, D. C., D. G. Williams, C. L Unkrich, J. F. Hogan, R. L Scott, K. R. Hultine, D. Pool, A. L Coes, and S. N. Miller. 2004. "Comparison of Methods to Estimate Ephemeral Channel Recharge, Walnut Gulch, San Pedro River Basin, Arizona." In *Groundwater Recharge in a Desert Environment: The Southwestern United States, Water Science and Application*, edited by F.M. Phillips, J.F. Hogan, and B. Scanlon, 77–99. Vol. 9. Washington, DC: American Geophysical Union.

Greenbaum, N., U. Schwartz, A.P. Schick, and Y. Enzell. 2002. “Paleofloods and the Estimation of Long Term Transmission Losses and Recharge to the Lower Nahal Zin Alluvial Aquifer, Negev Desert, Israel.” In *Ancient Floods, Modern Hazards: Principles and Applications of Paleoflood Hydrology*, edited by P.K. House, R.H. Webb, V.R. Baker, and D.R Levish, 311–328. Washington, USA: Amercan Geophysical Union.

Gu, R., and M. Deutschman. 2001. “Hydrologic Assessment of Water Losses in River.” *Journal of Water Resources Planning and Management* 127 (1): 6–12. doi:10.1061/(ASCE)0733-9496(2001)127:1(6).

Hacker, F. 2005. Model for Water Availability in Semi-Arid Environments (WASA): Estimation of Transmission Losses by Infiltration at Rivers in the Semi-arid Federal State of Ceará (Brazil), University of Postdam, Germany.

Huang, Y, X Chen, X. Chen, and G Ou. 2015. “Transmission Losses during Two Flood Events in the Platte River, South-central Nebraska.” *Journal of Hydrology* 520: 244–253. doi:10.1016/j.jhydrol.2014.11.046.

Hughes, D. 2009. “Simulating the Hydrology and Total Dissolved Solids (TDS) of an Ephemeral River in South Africa for Environmental Water Requirement Determinations.” *River Research and Applications* 25 (7): 850–860. doi:10.1002/rra.1188.

Hughes, D., and K. Sami. 1992. “Transmission Losses to Alluvium and Associated Moisture Dynamics in a Semiarid Ephemeral Channel System in Southern Africa.” *Hydrological Processes* 6 (1): 45–53. doi:10.1002/hyp.3360060105.

Hughes, D. A. 2019. “A Simple Approach to Estimating Channel Transmission Losses in Large South African River basins.Journal of Hydrology.” *Regional Studies* 25: 100619.

Ibrahim, M., D. Wisser, A. Ali, B. Dickkruger, O. Seidou, A. Mariko, and A. Afounda. 2017. “Water Balance Analysis over the Niger Inland delta-Mali: Spatio-temporal Dynamics of the Flooded Area and Water Losses.” *Hydrology* 4 (3): 40–63. doi:10.3390/hydrology4030040.

Jarihani, A.A., J.R. Larsen, J.N. Callow, T.R. McVicar, and K. Johansen. 2015. “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.” *Journal of Hydrology* 529: 1511–1529. doi:10.1016/j.jhydrol.2015.08.030.

Keppel, R.V., and K. Renard. 1962. “Transmission Losses in Ephemeral Stream Beds.” *Journal of the Hydraulics Division* 88 (3): 59–68. doi:10.1061/JYCEAJ.0000734.

Knighton, A.D., and G.C. Nanson. 1994. “Waterholes and Their Significance in the Anastomosing Channel System of Cooper Creek, Australia.” *Geomorphology* 9 (4): 311–324. doi:10.1016/0169-555X(94)90052-3.

Knighton, A.D., and G.C. Nanson. 2001. “An Event-based Approach to the Hydrology of Arid Zone Rivers in the Channel Country of Australia.” *Journal of Hydrology* 254 (1): 102–123. doi:10.1016/S0022-1694(01)00498-X.

Lane, L., M. Diskin, and K. Renard. 1971. “Input-output Relationships for an Ephemeral Stream Channel System.” *Journal of Hydrology* 13: 22–40. doi:10.1016/0022-1694(71)90198-3.

Lane, L.J. 1985. “Estimating Transmission Losses, Development and Management Aspects of Irrigation and Drainage Systems.” ASCE; 105–113.

Lane, L.J., V.A. Ferreira, and E.D. Shirley. 1980. “Estimating Transmission Losses in Ephemeral Stream Channels, Hydrology and Water Resources in Arizona and the Southwest.” Arizona: Nevada Academy of Science.

Lang, S., P. Hill, M. Scorah, and D. Stephens. 2015. “Defining and Calculating Continuing Loss for Flood Estimation.” In: 36thHydrology and Water Resources Symposium: The art and science of water. Engineers Australia, 193.

Lange, J. 2005. “Dynamics of Transmission Losses in a Large Arid Stream Channel.” *Journal of Hydrology* 306 (1): 112–126. doi:10.1016/j.jhydrol.2004.09.016.

Li, C., Z. Yang, G. Huang, Q. Tan, and Y. Cai. 2011. “Analysis of the Net Water Loss in the Main Reach of the Yellow River.” *International Journal of Environment and Pollution* 45 (1–3): 249–267. doi:10.1504/IJEP.2011.039100.

Lininger, K.B., and E.M. Latrubesse. 2016. “Flooding Hydrology and Peak Discharge Attenuation along the Middle Araguaia River in Central Brazil.” *Catena* 143: 90–101. doi:10.1016/j.catena.2016.03.043.

McMahon, T., M. Peel, L. Lowe, R. Srikanthan, and T. McVicar. 2013. “Estimating Actual, Potential, Reference Crop and Pan Evaporation Using Standard Meteorological Data: A Pragmatic Synthesis.” *Hydrology and Earth System Sciences* 17 (4): 1331–1363. doi:10.5194/hess-17-1331-2013.

McMahon, T., R. Murphy, M. Peel, J. Costelloe, and F. H. Chiew. 2008. “Understanding the Surface Hydrology of the Lake Eyre Basin: Part 2, Streamflow.” *Journal of Arid Environments* 72 (10): 1869–1886. doi:10.1016/j.jaridenv.2008.06.001.

McMahon, T. A., B. L. Finlayson, A. T. Haines, and R. Srikanthan. 1992. *Global Runoff -continental Comparisons of Annual Flows and Peak Discharges*. Stuttgart, Germany: Catena Verlag.

Mohammadi, A., D. Ryu, and J. Costelloe. 2013. “Mapping of Flow Paths in Large, Anastomosing Arid Zone Rivers: Cooper Creek, Australia.” *Modelling and Simulation Society of Australia and New Zealand* 2485–2491.

Montazeri, M., D. Way, M. Gibbs, C. Bloss, and C. Wood. 2011. “Coorong South Lagoon Flow Restoration Project: Hydrological Modelling and Transmission Loss Analysis. Technical Note 2011/05 Department for Water; Government of South Australia.”

Morin, E., T. Grodek, O. Dahan, G. Benito, C. Kulls, Y. Jacoby, G. Van Langenhove, M. Seely, and Y. Enzel. 2009. “Flood Routing and Alluvial Aquifer Recharge along the Ephemeral Arid Kuiseb River, Namibia.” *Journal of Hydrology* 368 (1–4): 262–275. doi:10.1016/j.jhydrol.2009.02.015.

Murray-Darling Basin Authority. 2019. *Losses in the River Murray System 2018-19*. Canberra: Murray-Darling Basin Authority.

Nguyen, V.T., J. Dietrich, B.and Uniyal, and A.D Tran. 2018. “Verification and Correction of the Hydrologic Routing in the Soil and Water Assessment Tool.” *Water* 10 (10): 1419–1428. doi:10.3390/w10101419.

Osterkamp, W. R., L. J.C. Lane, and M. Menges. 1995. “Techniques of Ground-water Recharge Estimates in Arid/semi-arid Areas, with Examples from Abu Dhabi.” *Journal of Arid Environments* 31: 349–369. doi:10.1016/S0140-1963(05)80038-2.

Pacheco-Guerrero, A., D. Goodrich, J. González-Trinidad, H. Júnez-Ferreira, and C. Bautista-Capetillo. 2017. "Flooding in Ephemeral Streams: Incorporating Transmission Losses." *Journal of Maps* 13 (2): 350–357. doi:10.1080/17445647.2017.1305303.

Rao, C.X., and E.P. Maurer. 1996. "A Simplified Model for Predicting Daily Transmission Losses in A Stream Channel." *Water Resources Bulletin* 32 (6): 1139–1146. doi:10.1111/j.1752-1688.1996.tb03484.x.

Reid, I., J.B. Laronne, and D.M. Powell. 1998. "Flash-flood and Bedload Dynamics of Desert Gravel-bed Streams." *Hydrological Processes* 12 (4): 543–557. doi:10.1002/(SICI)1099-1085(19980330)12:4<543::AID-HYP593>3.0.CO;2-C.

Reid, I., and L.E. Frostick. 2011. *Channel Form, Flows and Sediments of Endogenous Ephemeral Rivers in Deserts. Arid Zone Geomorphology: Process, Form and Change in Drylands*, 301–332. Third ed, Wiley, UK.

Riddell, E.S., J.M. Nel, S. Gokool, C. Jarmain, R. Raubenheimer, T. Strydom, and A. Swemmer, 2017. Quantification of Transmission Losses along the Letaba River for Improved Delivery of Environmental Water Requirements (Ecological Reserve). Water Research Commission Report, Project Number K5/2338, South Africa.

Rivaz, N., and S.H. Musavi-Jahromi. 2012. "Estimation of Transmission Losses in the Ephemeral Rivers Applying MIKE11 (Case Study: Khoshk River, Shiraz, Iran)." *Archives Des Sciences* 65 (8): 2–12.

Saber, M., T. Hamaguchi, T. Kojiri, K. Tanaka, and T. Sumi. 2013. "A Physically Based Distributed Hydrological Model of Wadi System to Simulate Flash Floods in Arid Regions." *Arabian Journal of Geosciences* 8 (1): 143–160. doi:10.1007/s12517-013-1190-0.

Schoener, G. 2017. "Quantifying Transmission Losses in A New Mexico Ephemeral Stream: A Losing Proposition." *Journal of Hydrologic Engineering* 22 (3): 05016038. doi:10.1061/(ASCE)HE.1943-5584.0001473.

Schreiner-McGraw, A.P., H. Ajami, and E.R. Vivoni. 2019. "Extreme Weather Events and Transmission Losses in Arid Streams." *Environmental Research Letters* 14 (8): 084002.

Schwartz, U., A.P. Schick, and Y. Enzel. 2002. "Paleofloods and the Estimation of Long Term Transmission Losses and Recharge to the Lower Nahal Zin Alluvial Aquifer, Negev Desert, Israel. Ancient Floods, Modern Hazards." *Principles and Applications of Paleoflood Hydrology* 1: 311.

Shanafield, M., and P.G. Cook. 2014. "Transmission Losses, Infiltration and Groundwater Recharge through Ephemeral and Intermittent Streambeds: A Review of Applied Methods." *Journal of Hydrology* 511: 518–529. doi:10.1016/j.jhydrol.2014.01.068.

Sharma, K., and J. Murthy. 1994. "Estimating Transmission Losses in an Arid Region." *Journal of Arid Environments* 26 (3): 209–219. doi:10.1006/jare.1994.1024.

Sharma, K., and J. Murthy. 1995. "Hydrologic Routing of Flow in Arid Ephemeral Channels." *Journal of Hydraulic Engineering* 121 (6): 466–471. doi:10.1061/(ASCE)0733-9429(1995)121:6(466).

Sharp, A., and K. Saxton. 1962. "Transmission Losses in Natural Stream Valleys." *Journal of the Hydraulics Division* 88 (5): 121–142. doi:10.1061/JYCEAJ.0000770.

Shaw, J.R., and D.J. Cooper. 2008. "Linkages among Watersheds, Stream Reaches, and Riparian Vegetation in Dryland Ephemeral Stream Networks." *Journal of Hydrology* 350 (1): 68–82. doi:10.1016/j.jhydrol.2007.11.030.

Shentsis, I., L. Meirovich, A. Ben-Zvi, and E. Rosenthal. 1999. "Assessment of Transmission Losses and Groundwater Recharge from Runoff Events in a Wadi under Shortage of Data on Lateral Inflow, Negev, Israel." *Hydrological Processes* 13 (11): 1649–1663. doi:10.1002/(SICI)1099-1085(19990815)13:11<1649::AID-HYP834>3.0.CO;2-N.

Sophocleous, M. 2002. "Interactions between Groundwater and Surface Water: The State of the Science." *Hydrogeology Journal* 10 (1): 52–67. doi:10.1007/s10040-001-0170-8.

Sorman, A.U., and M.J. Abdulrazzak. 1993. "Infiltration-recharge through Wadi Beds in Arid Regions." *Hydrological Sciences Journal* 38 (3): 173–186. doi:10.1080/02626669309492661.

Stewardson, M.J., and F. Guarino. 2018. "Basin-scale Environmental Water Delivery in the Murray–Darling, Australia: A Hydrological Perspective." *Freshwater Biology* 43 (8): 967–985.

Thomas, C.L., A.E. Stewart, and J.E. Constantz. 2000. "Determination of Infiltration and Percolation Rates along a Reach of the Santa Fe River near La Bajada, New Mexico, US Dept. Of the Interior, US Geological Survey; Information Services."

Tooth, S. 2000. "Process, Form and Change in Dryland Rivers: A Review of Recent Research." *Earth-Science Reviews* 51 (1): 67–107.

Tooth, S., and G.C. Nanson. 2011. "Distinctiveness and Diversity of Arid Zone River Systems. Arid Zone Geomorphology." In *Process, Form and Change in Drylands*, edited by D.S.G. Thomas, 269–300. Third ed. Chichester, UK: Wiley and Blackwell.

Tooth, S. 2013. "Dryland Fluvial Environments: Assessing Distinctiveness and Diversity from a Global Perspective." In *Treatise on Geomorphology*, edited by J. F. Shroder, 612–644, Vol. 9 First. San Diego.: Elsevier.

Walters, M.O. 1990. "Transmission Losses in Arid Region." *Journal of Hydraulic Engineering* 116 (1): 129–138. doi:10.1061/(ASCE)0733-9429(1990)116:1(129).

Wu, G., X. Zhen, and G. Lin. 2011. "Field Experimental Study on Infiltration in Seasonal River Channels." *Arid Zone Res* 28: 74–78. doi:10.3724/SP.J.1148.2011.00074.