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RESEARCH ARTICLE

Assessing the variation of river channel reach inflows on transmission losses

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Abstract

Arid and semi-arid regions are characterized by limited water availability throughout the year and highly variable streamflows. River channel transmission losses add another uncertainty to the complex flow regimes. However, the contribution of different factors influencing to transmission losses is poorly understood. In this work we determined whether variations in river channel transmission losses along five reaches of varying lengths could be related to reach inflows in Runde River catchment in Zimbabwe. We directly estimated transmission losses as the difference between reach inflow and outflow discharges. Using simple bivariate regression equations, channel transmission losses were modeled as response variables while reach inflows were the predictor variables. Our results indicate statistically significant positive relationships ($p = .000$, $R^2 > 0.05$) between inflows and transmission losses for all minor, moderate, and major flow events. This simple approach can be applied in similar settings to understand the variations in transmission losses.

KEYWORDS

transmission losses, river reach inflows, regression, model, Runde River catchment

1 | INTRODUCTION

The decrease of flows along river reaches due to transmission losses is a common phenomenon in all environmental settings. However, the effects of transmission losses are particularly significant in arid and semi-arid environments where there is a critical shortage of water (Brunner et al., 2009; Mujere et al., 2020). While the processes that cause river channel transmission losses, such as evapotranspiration, ponding in channel depressions, infiltration into channel bed and banks, overbank flows, artificial withdrawals, and diversions from channels, are well understood, the mechanisms and drivers of losses are less understood (Brunner et al., 2009; Hughes, 2019). This knowledge gap adds to the challenge of hydrological modeling in arid and semi-arid areas. Besides the modeling challenges, transmission losses remain critical aspects of the dryland hydrologic budget and, hence, need special attention.

Nevertheless, sound hydrologic planning requires a wide range of information that accounts for spatial and temporal flow variability. Understanding the drivers and variation of transmission losses in arid and semi-arid areas is not only significant from a hydrologic viewpoint but also from socio-economic, policy, and environmental perspectives. In fact, ecosystems are extremely sensitive to hydrological variations because they depend on river flow to conserve their composition and structure. Losses are important in reducing flood peaks resulting from sporadic storms, which are common in arid and semi-arid regions (Lange, 2005; Shanafield & Cook, 2014). Transmission losses also support riparian vegetation and recharge local aquifers during seepage along channel beds and banks (Abdulrazzak & Sorman, 1994; Shentsis & Rosenthal, 2003). By recharging groundwater, underground water resources are sustained, thus supplementing the highly stressed surface water resources. Thus, it is prudent to have an accurate estimation of transmission losses for modeling surface water supply and demand, stream water requirements, groundwater-surface water interactions, runoff hydrographs, and prediction of runoff peak flows in arid and semi-arid catchments (Shanafield & Cook, 2014).

2 | MODELING RIVER CHANNEL TRANSMISSION LOSSES

In situations where measuring equipment and lots of data are available, complex models such as flow routing, water budget, and controlled field experiments are used to estimate transmission losses. Some of the approaches rely on data from field measurements and other modeling techniques. Of late, the models have been implemented in a GIS environment to show spatial variations of losses (Kammer, 1997, 1998; Walters, 1990). Nevertheless, the drawback in using complex models is that most areas in arid and semiarid environments are not accessible and there is shortage of flow measuring equipment.

When measuring equipment and lots of data are available from field measurements and other modeling techniques, complex models such as flow routing, water budget, and controlled field experiments are used to estimate transmission losses. Of late, the model results have been implemented in a GIS to show spatial variations of losses (Li et al., 2011; Sharma & Murthy, 1995; Walters, 1990). Nevertheless, the drawback in using complex models is that most areas in arid and semi-arid environments are not accessible and there is shortage of flow measuring equipment.

In situations where data are available from direct measurements, transmission losses along river channels are easily estimated as the difference between observed reach inflow and outflow while incorporating the contribution of tributary inflow and channel precipitation (Lane et al., 1980; Min et al., 2013; Telvari et al., 1998). This approach is simple, quick, and straightforward although securing and installing adequate measurement remains a challenge due to resource and accessibility constraints.

Where direct observations are often not feasible, simple deterministic models such as differential equations and regression equations are commonly used to predict the dynamics of transmission losses from flow and channel characteristics (Abdulrazzak & Sorman, 1994; Reid & Frostick, 2011; Sharma & Murthy, 1995; Sharma & Murthy, 1998). Regression equations are site-specific, straightforward to implement, require less information and are good estimators of channel loss when regression coefficients are within proper constraints (Min et al., 2013; Mujere et al., 2021; Parsons et al., 1999). Studies have observed significant relationships between river reach channel transmission loss and reach inflow (Abdulrazzak & Sorman, 1994; Reid & Frostick, 2011; Sharma & Murthy, 1995; Sharma & Murthy, 1998), channel width (Walters, 1990), and reach length (Kammer, 1997, 1998). However, the accuracy and reliability of model results are often compromised by the scarcity of observational flow data and/or small sample sizes along ephemeral river systems (Shanafield & Cook, 2014). Given some of the aforementioned difficulties, predicting transmission losses has remained a major research challenge.

Investigating the variations of river reach inflow and its effects on transmission losses is vital to understanding the influence of climate and non-climate fluctuations on river hydrologic systems (Mujere et al., 2021). Awareness of flow regimes is essential for surface water resource planning, design, and management as well as improving flood protection (Boroto & Gorgens, 2003; Costelloe et al., 2003, 2007; Saber et al., 2015; Walters, 1990). Furthermore, decision makers and planners need accurate information on transmission losses for assessing the efficiency and viability water resource infrastructure and managment strategies. Transmission loss analysis involves forecasting the expected occurence of low and high loss magnitudes over spatial and temporal scales.

3 | MATERIALS AND METHODS

3.1 | Description of the study area

The Runde River catchment (Figure 1) is located in south-eastern Zimbabwe in a semi-arid landscape covering an area of 41,056 km^2 (Mujere et al., 2020). It lies in one of the driest parts of Zimbabwe, covering 22% of the country. Almost 40% of this catchment is occupied by communal lands. In 2012, the population of the catchment was 1.5 million people, of which 89% lived in rural areas and the remainder lived in urban areas (ZimStat, 2012).

The catchment is underlain by basement complex rocks, which form localized aquifers with limited baseflows. The northern upper reaches are covered by sandy soils from the weathering of granite, while the southern parts comprise alluvial deposits on valley slopes (Mujere et al., 2020). The presence of highly leaching sandy and alluvial soils enhances channel infiltration rates, thus reducing surface water flow.

The catchment is virtually dry with an aridity index (ratio of mean annual precipitation to potential evaporation) of 0.4. It experiences seasonal rainfall from mid-November to March. Almost 95% of the rainfall is received from November to February, thus making the rest of the year dry. As a result, river flows occur during the rainy period, while during the rest of the year there are low or no flows on most rivers. The catchment experiences a mean annual

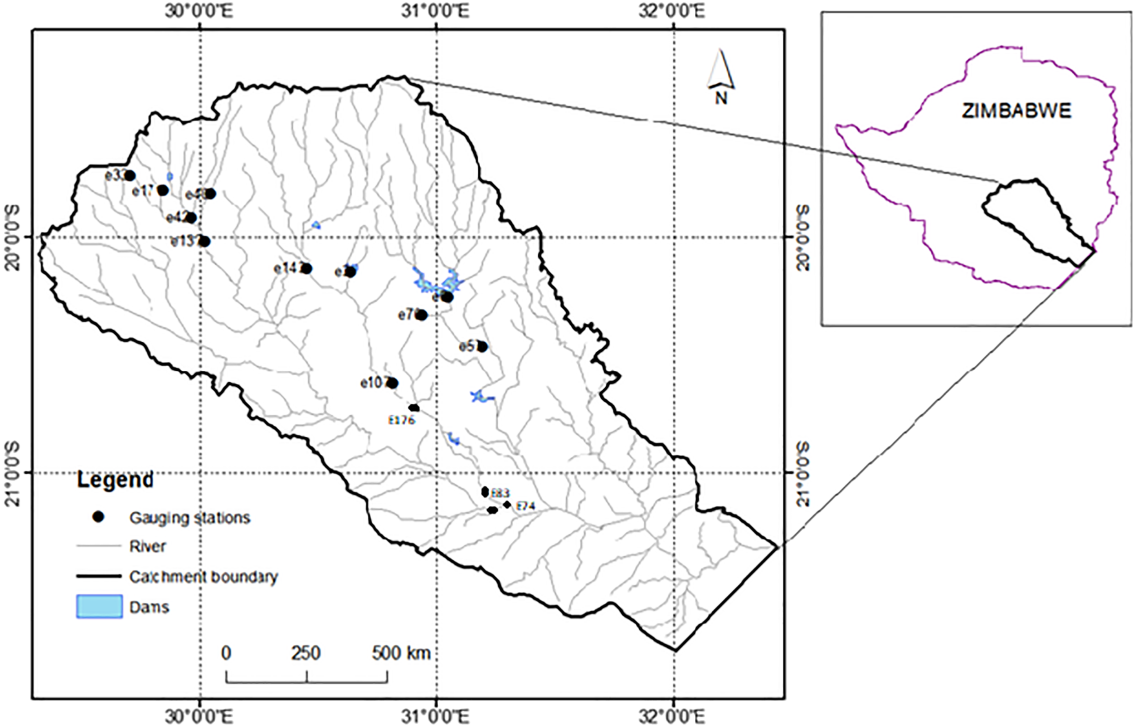

FIGURE 1 Location of Runde catchment in Zimbabwe and selected river reaches

temperature of 19.4°C (Mujere et al., 2020). Groundwater and water harvested in reservoirs are critical water sources for irrigation, industry, municipalities, and domestic needs during most parts of the year.

3.2 | Methods

The main consideration in selecting the five river reaches in the study was the availability of upstream and downstream flow data. This enabled quick, accurate, and easy estimation of channel transmission losses along each river reach. Discussions were held with the Runde catchment hydrologist, a staff member of the Zimbabwe National Water Authority (ZINWA) to identify flow measuring stations with accurate and reliable flow data. The organization, has for each gauging station in the country, a file documenting the maintenance of the station and the accuracy of rating curves. The reports of these assessments were considered in selecting flow measuring stations along river reaches. River flow measurements in the catchment are done using flumes and weirs that are equipped with automatic recorders. Recording charts were changed regularly, every week. For the selected stations, the flow ratings have remained fairly stable because little amounts of sediment have accumulated upstream of the hydraulic structures. The downstream gradients are high, thus preventing backwater effects on the water levels (Runde catchment hydrologist, pers. comm., 2017). In addition, data undergoes rigorous screening before being given to the public. Thus, the data used in this study were regarded to be of high quality.

Reach 1 lies between the confluence of rivers gauged by stations E3 and E143, and E107. Reach inflows are recorded at stations E3 and E143, while outflows are recorded at station E107. We grouped 80 inflow events into minor (<10 m^3/s, $n = 33$), moderate (10 to 100 m^3/s, $n = 32$), and major (100–734.43 m^3/s, $n = 15$).

For reach 2, we calculated the reach inflow as a sum of flows recorded at upstream gauging stations E33, E171, E40, and E42, and downstream station E137. We grouped 435 inflow events into minor (0.01 to 0.49 m^3/s, $n = 82$), moderate (0.5 to 0.99 m^3/s, $n = 180$), and major events (1 to 26.36 m^3/s, $n = 163$).

Reach 3 lies between the upstream stations E6 and E70, and the downstream station, E57. We grouped the 837 reach inflow events into minor (0.30 to 0.49 m^3/s, $n = 75$), moderate (0.5 to 9.9 m^3/s, $n = 587$), and major (≥ 10 m^3/s, $n = 175$).

Reach 4 lies between the upstream gauging station, E107, and the downstream station, E176. We grouped the 194 reach inflows into minor (0.01–9.03 m^3/s, $n = 57$), moderate (9.84–93.32 m^3/s, $n = 113$), and major events (93.79–195.85 m^3/s, $n = 24$).

Reach 5 lies between upstream gauging stations E84 and E83 and the downstream gauging station E74. We grouped 343 daily reach inflows into minor events (0.11–0.95 m^3/s, $n = 212$), moderate events (1.0–9.96 m^3/s, $n = 87$), and major events (11.29–420.65 m^3/s, $n = 44$).

We used simple regression equations to determine the variation of transmission losses with reach inflows of different magnitudes along four channel reaches in the Runde River catchment in Zimbabwe. For transmission loss to take place, upstream flow should exceed downstream flow. Thus, we selected data from flow events in which the reach inflow at the upstream gauging stations exceeded the flow measured at downstream gauging stations. We directly estimated the amount of transmission loss by subtracting the flow measured downstream from the flow measured upstream of the river reach. For each event, transmission loss (T) along a channel reach was calculated as a difference between inflow Q_i and channel outflow Q_o using the equation:

$$T = Q_i - Q_o \tag{1}$$

We described every event according to T as follows:

1. If $T < 0$, then there was no transmission loss because reach outflow exceeds inflow. Thus, transmission losses were compensated by inflow from the drainage area or channel precipitation such that reach outflow exceeded reach inflow.
2. If $T = 0$, then transmission losses were approaching zero, thus reach inflow and outflow were equal and negligible transmission losses occurred
3. If $T > 0$, then transmission losses would have occurred since inflow from the upstream gauges exceeded outflow at the downstream gauge. In situations when $T = Q_i$, then all reach inflows are lost as transmission loss.

In situations where we had more than one stream contributing to reach outflow, we estimated inflows as the sum of flows measured at upstream gauging stations.

Before determining statistical relationships between transmission losses as response variables and reach inflows as predictor variables, we tested for data normality using the Kolmogorov–Smirnov test. We found that the *p*-values were less than the significance level, $\alpha = .05$ ($p > .05$) indicating that data followed a normal distribution. Thus, we used linear models to relate reach inflows to transmission loss.

In modeling the relationship between river reach transmission losses and inflows, we plotted inflows as predictor variables against losses as response variables on scatter plots. We then used simple regression equations to determine the relationship between transmission losses and reach inflows for all minor, moderate, and major inflow events. We determined the significance of the relationships by considering the *p*-value at the significance level, $\alpha = .05$. The relationships were regarded to be significant when the *p*-values were less than the significance level ($p < .05$) and vice versa.

4 | RESULTS

Figure 2 shows statistically significant ($p = .000$) positive linear relationships between river reach inflows and transmission losses along reach 1. During minor events, almost 97% of the reach inflows were lost along the channel, hence did not reach the downstream gauging station, E107. Whereas 16% of the reach inflows during moderate events resulted in zero flows at the downstream gauging station, E107.

Figure 3 shows statistically significant ($p = .000$) relationships between river reach inflows and transmission losses along reach 2. Almost 48% of reach inflows were lost before reaching the reach outlet gauging station during minor events. About 19% of reach inflow events resulted in zero flows at the reach outlet gauging station, E137, as a result of transmission losses along the channel.

Figure 4 shows a statistically significant ($p = .000$) positive linear relationship between inflowes and transmission losses along reach 3. The mean of reach inflows is 27.48 m^3/s, a standard deviation of 85.21 m^3/s, and a range of 713.76 m^3/s. Transmission losses range from 0.03 m^3/s to 300.52 m^3/s with a mean of 7.87 m^3/s and a standard deviation of 30.36 m^3/s.

Figure 5 shows the relationships between river reach inflows and transmission losses during along reach 4. Reach inflows have a range of 195.8 m^3/s, a mean of 52.38 m^3/s, and a standard

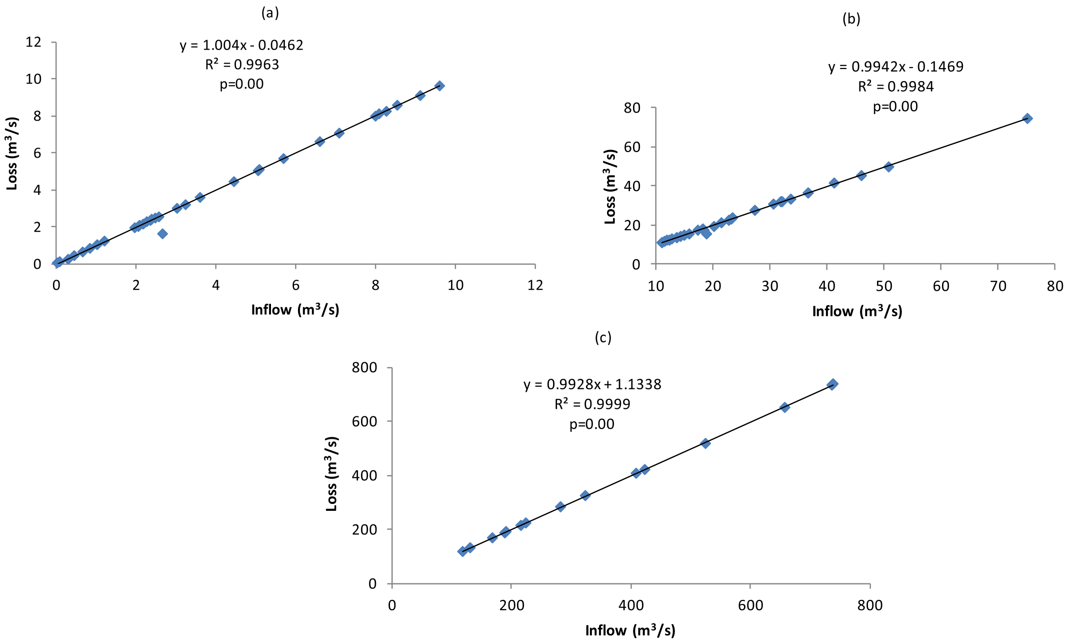

FIGURE 2 Statistically significant ($p < .05$) relationships between river reach inflow and transmission loss during minor, medium, and major flow events

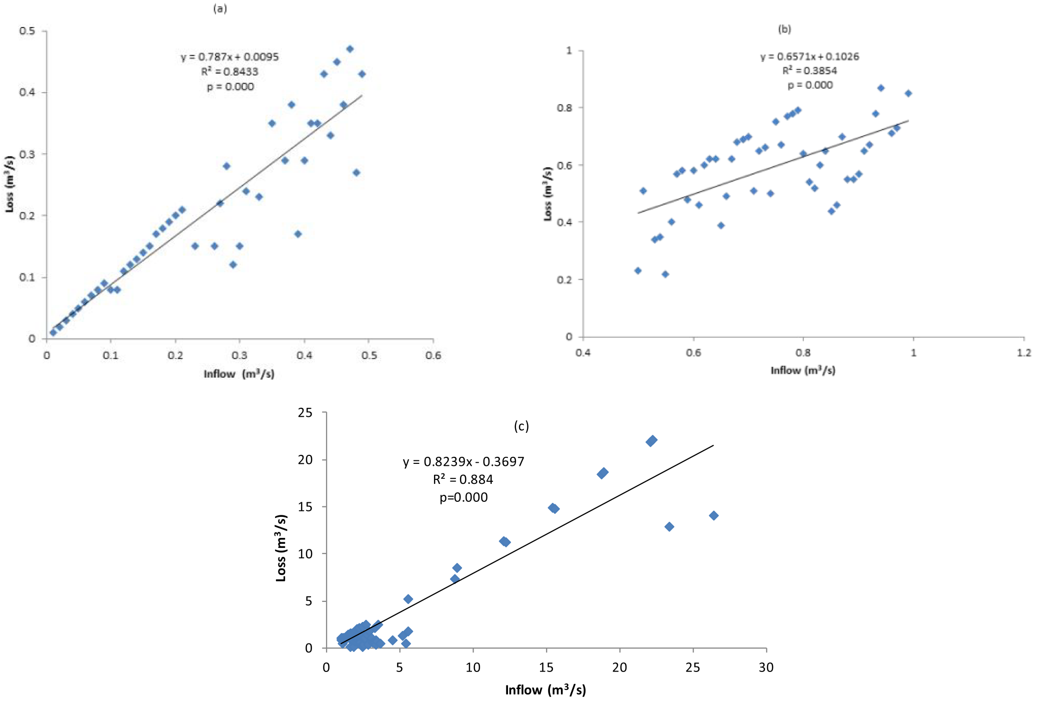

FIGURE 3 Statistically significant ($p < .05$) relationships between river reach inflow and transmission loss during (a) minor, (b) moderate, and (c) major flow events

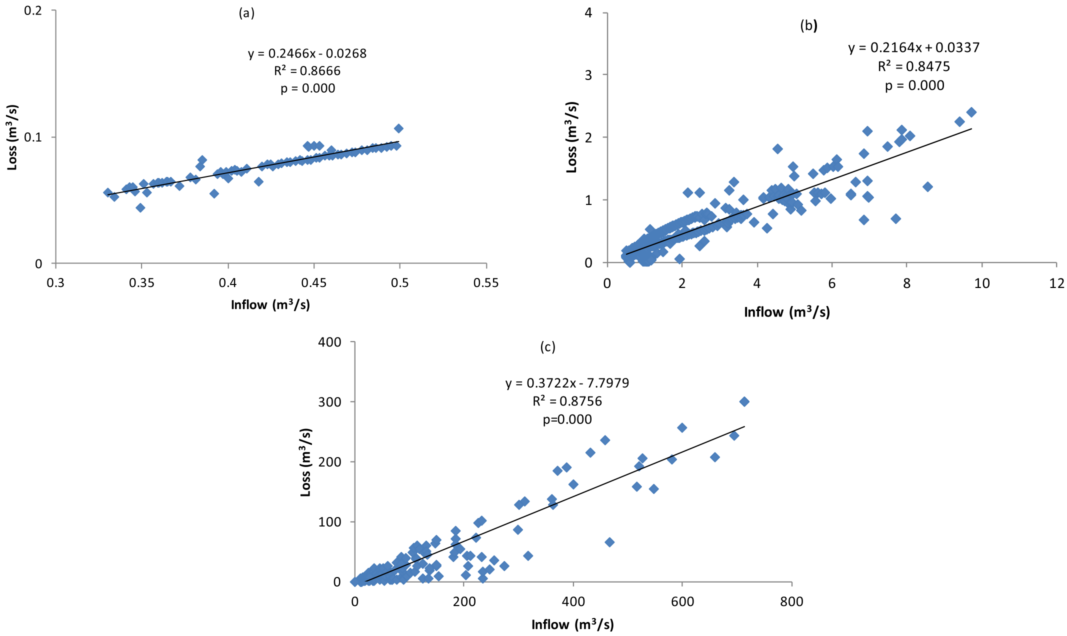

FIGURE 4 Statistically significant ($p < .05$) relationships between river reach inflow and transmission loss during (a) minor, (b) moderate, and (c) major flow events

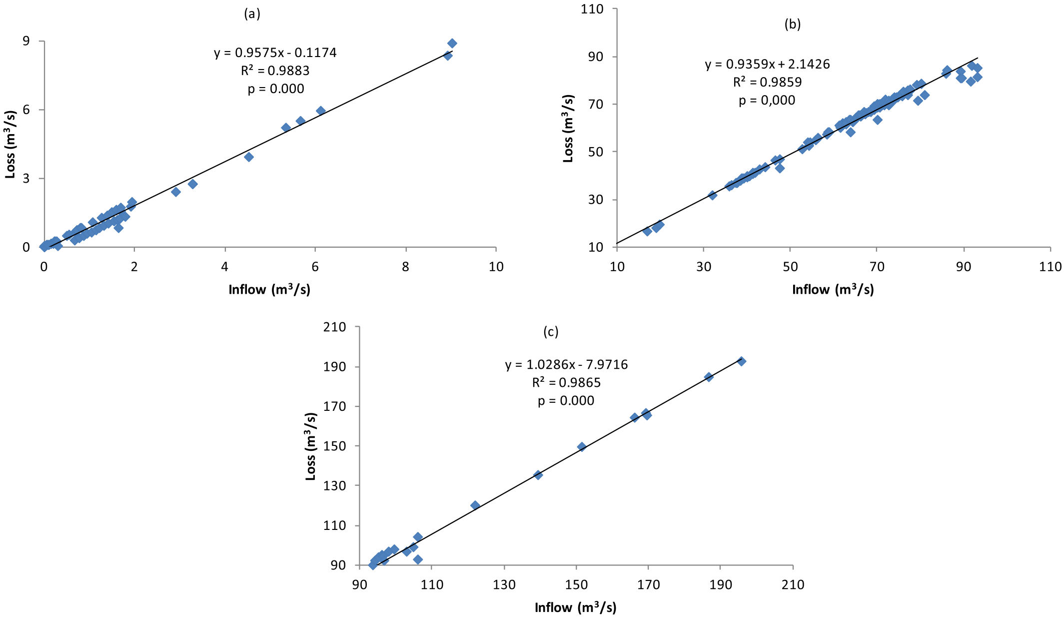

FIGURE 5 Statistically significant ($p < .05$) relationships between river reach inflow and transmission loss during (a) minor, (b) moderate, and (c) major flow events

deviation of 41.6 m^3/s. Transmission losses vary from 0.01 m^3/s to 192.3 m^3/s with a mean of 50.6 m^3/s and a standard deviation of 40.3 m^3/s. During minor events, almost 32% of the inflows were lost along the channel segment so they could reach the outflow gauging station.

Figure 6 shows a statistically significant ($p = .000$) positive linear relationship between reach inflows and transmission losses along reach 5. Reach inflows have a range of 420.56 m^3/s, a mean of 14.48 m^3/s, and a standard deviation of 58.96 m^3/s. Transmission losses vary from 0.05 m^3/s to 298.26 m^3/s with a mean of 7.5 m^3/s and a standard deviation of 26.59 m^3/s. During minor events, almost 97% of the inflows were lost along the channel segment, so could reach the outflow gauging station. Also, during moderate events, 49% of the inflows failed to reach the inflow gauge due to transmission losses.

5 | DISCUSSION

In this study, we used regression models to determine relationships between transmission losses and reach inflows. Our results show transmission losses increase with flow magnitude, maybe due to the increase in infiltration as a result of the high hydraulic head at the surface. The difference in hydraulic head is a fundamental physical principle which explains high transmission losses at high stream discharge hydraulic (Abdulrazzak & Sorman, 1994; Jarihani et al., 2015). The statistically significant linear relationships between transmission loss-reach inflow relationships obtained in this study are consistent with those developed in previous studies across various spatial and temporal scales (Nyadiwa et al., 1997; Reid & Frostick, 2011; Sharma & Murthy, 1995; Sharma & Murthy, 1998). However, studies by Walters (1990), Morin et al. (2009) have shown significant power relationships between reach inflows and transmission losses.

The study has also shown that the proportion of transmission losses decreases from minor to major inflow events. This agrees with findings from a study along the 180 km reach of the Diamantina River in Australia, which showed a negative linear relationship between

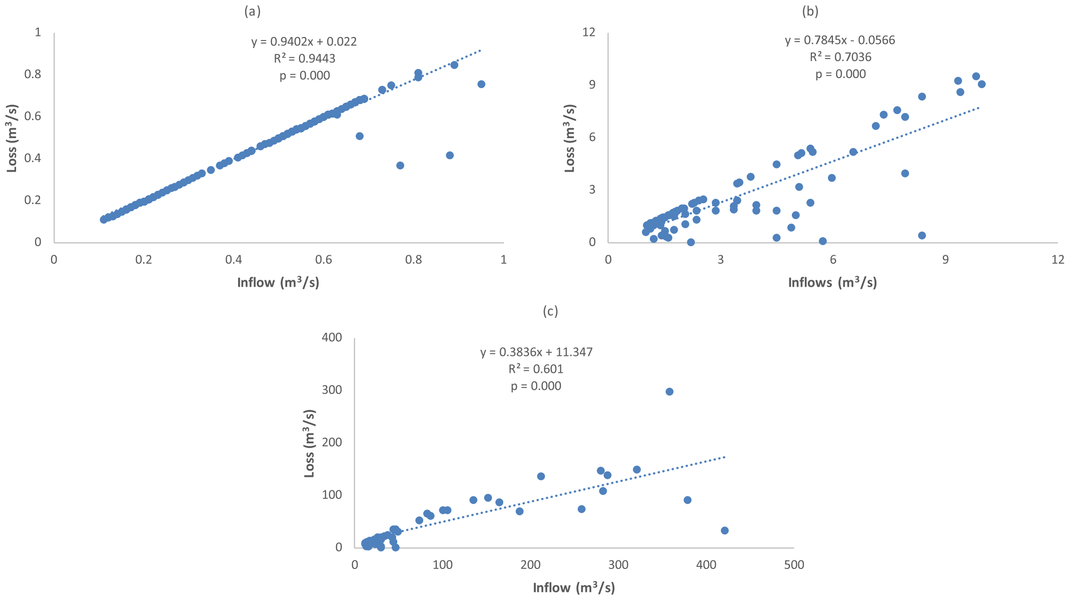

FIGURE 6 Statistically significant ($p < .05$) relationships between river reach inflow and transmission loss during (a) minor, (b) moderate, and (c) major flow events

transmission loss and flood discharge (Jarihani et al., 2015). Low peak flows resulted in large losses of up to 68% of the inflows, while high peak flows resulted in low losses of 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.

Our findings also show that in 9 out of all 15 events, more than 90% of the variation in transmission losses could be explained by variation in reach inflows. Exceptions are made during minor and moderate events along reach 2 and, moderate and major events along reach 3 and reach 5. Reach inflows explain only 39% of the variations in transmission loss along reach 2 during moderate events. Inflows for reach 2 and reach 3 explain 84% of the variations in transmission losses during minor and moderate events, respectively. Along reach 5, the research observed that during moderate events, variations of reach inflows explain 70% of the variations in losses. Whereas, during major events, 60% of the variations in transmission losses could be explained by reach inflows. The unexplained variations of transmission losses can be explained by other factors not considered in this study. These factors include precipitation, reach length, channel slope, depth of bed material, and sinuosity ratio.

From this discussion, it implies that regression models are important tools in assessing variations of channel transmission losses where there is no lateral tributary inflows and groundwater contribution between along river reaches. However, there are some uncertainties associated with this approach. The presence of lateral reach inflows from ungauged tributaries, groundwater recharge, and channel precipitation between upstream and downstream gauging stations provide errors in estimating transmission loss. When these processes occur, transmission loss values would be under-estimated even if reach inflows exceed outflows.

Accordingly, this research only used five river reaches, making results limited in terms of global or regional applicability. Increasing the number of reaches from different environmental settings would allow results to be extrapolated to other areas. Nevertheless, our analysis provides evidence of the significant influence of reach inflow on transmission loss.

6 | CONCLUSION

Ephemeral river reaches are characterized by discharge decreasing downstream due to transmission losses unless augmented by tributary flows. Accurate and reliable information on river channel transmission losses is useful to understand the dynamics of surface runoff volumes and groundwater recharge in arid and semi-arid regions. Yet, most estimation techniques require either extensive data inputs or extensive field work, thus limiting their usefulness to planners. Estimation techniques that have been employed include field and empirical methods based on physical observations, statistical, and physical modeling approaches.

In this study, we determined whether the variations in river reach transmission losses can be related to reach inflows along five reaches in Runde River catchment in Zimbabwe. The results show that despite the variations in flow events, river losses are significantly related to reach inflows. Therefore, this study demonstrates the usefulness of a simple approach in showing how different flow magnitudes affect channel losses. Indeed, many reports indicate an increase in transmission losses with increasing flows without categorizing not categorized the inflows. This simple analysis can be applied to similar data-scarce dryland regions to understand how transmission losses vary.

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