Hydrological functioning of cattle ranching impoundments in the Dry Chaco rangelands of Argentina

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ABSTRACT

Rainwater harvesting and associated storage is essential for cattle ranching in the drylands of Argentina and elsewhere. This is the first study to attempt to quantify the hydrological inflows and losses from rainwater harvesting impoundments. To address the direct effect of cattle within impoundments, a typical cattle-affected impoundment was instrumented and compared with that of a similar impoundment but without cattle access. Analysis of the storage dynamics with reference to the controlling variables demonstrated the highly episodic nature of the generation of infiltration-excess overland flow that recharged the impoundments. The impoundments experienced 43 and 35% of storage loss to open-water-evaporation for the cattle-affected and control impoundments, respectively. Critically, the cattle-effected impoundment lost only 15% of storage to leakage (after cattle consumption was taken into account), while the control lost 65% of its water to basal leakage. Indeed systems modelling of the rainfall-storage dynamics showed that the cattle-affected impoundment, despite consumption by 300 cows, maintained water in the impoundment (per a unit input of rainfall) for longer than the control (a 65- versus 25-day residence time). These results highlight the unintended beneficial effect of cattle trampling on the floor of the impoundment reducing leakage losses.

Key words | arid, ecohydrology, grazing, livestock, rainwater harvesting, runoff

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INTRODUCTION

Extensive livestock production occupies one-third of the global land area and represents a key economic activity in low- and middle-income countries (Schimel 2010; Robinson *et al.* 2014). Given that most livestock systems are located in arid and semi-arid regions (hereafter drylands), water is the main constraint to production due to the shortage of palatable forage and limited access to drinking water for the cattle (Evenari *et al.* 1971; UNEP 2009). In the case of

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forage shortage, there are several management practices to consider, such as adjusting stocking rates (Ganskopp & Bohnert 2009; Fernández *et al.* 2015). However, water supply represents a crucial limitation for cattle survival (Ganskopp 2001; Bailey 2005) and it has been historically overcome by capturing infiltration-excess overland flow during rain events, so called 'rainwater harvesting' (Lavee *et al.* 1997; Oweis & Hachum 2009; Denison & Wotshela 2012). Huxman *et al.* (2004), Newman *et al.* (2006) and Jobbágy *et al.* (2008) have shown that this is feasible in dry and flat sedimentary landscapes where infiltration-excess overland flow may represent less than 5% of rainfall inputs. Infiltration-excess overland flow is surface flow on slopes (rather than channels) created when short-term rainfall intensities locally (in time and space) exceed the infiltration capacity of the soil (equivalent to the saturated hydraulic conductivity of the soil surface).

By definition, rainwater harvesting comprises of capturing, storing and then using infiltration-excess overland flows for water supply (Critchley *et al.* 1991; Fox & Rockström 2000). Most rainwater harvesting systems have a well-defined area upslope of an impoundment, where infiltration-excess overland flow is generated (Boers & Ben-Asher 1982; Pandey *et al.* 2003). Each impoundment may be a natural topographic depression or man-made excavation with embankments (Glendenning *et al.* 2012; Adham *et al.* 2016). In very flat landscapes it can be difficult to determine the exact contributory area of an impoundment because it is hard to define topographic divide and because of the enhanced role of preferential pathways of vehicle roads or cattle trails that may connect distal areas with the impoundment (Pandey *et al.* 2003; Magliano *et al.* 2015c). The generation of infiltration-excess overland flow is, however, enhanced by the presence of the high-intensity convective rainfall that characterizes semi-arid regions.

The Dry Chaco rangelands of northern Argentina (also known as Arid Chaco) is ~10 million hectares of sedimentary plain dominated by native dry woodlands (Cabrera 1976; Oyarzabal *et al.* 2018). In this region, rainwater harvesting systems used for cattle ranching are typically composed of a man-made impoundment associated with a contributory area crossed by cattle trails and vehicle roads (Karlin *et al.* 2013; Magliano *et al.* 2015c). Impoundments, with typical dimensions of approximately 50 × 80 m, consist of arched embankments built 2–4 m above the ground with an open section that allows entry of the infiltration-excess overland flow. Cattle drink water directly from within the impoundment so trampling the floor of the impoundment (in addition to trampling of the access points and contributory catchment) may be important. Cattle trails include networks of tracks characterised by bare and compacted ground that converges onto the open section of the impoundment. They are created by cattle as they move daily from grazing sites to the impoundments (George *et al.* 2004; Ganskopp & Bohnert 2009; Richardson & Rejmánek 2011; Karlin *et al.* 2013). These trails are often associated with an overgrazed surface zone close to the open side of the impoundment that is sometimes called the 'piosphere' or zone of focused impact of grazing animals on soils and vegetation (Macchi & Grau 2012; Chillo *et al.* 2015). Vehicle tracks are also present in the contributory catchments and are typically unpaved, slightly depressed roadways. There is some evidence that undisturbed Dry Chaco woodlands do not generate infiltration-excess overland flow that is able to travel more than a few metres (Aguilera *et al.* 2003; Kunst *et al.* 2003; Magliano *et al.* 2016; Magliano *et al.* 2015a), highlighting the importance of the cattle trails and vehicle tracks to generate the infiltration-excess overland flow that fills the impoundments built for cattle water supply.

Despite its great importance to cattle production in Dry Chaco rangelands, there is little scientific knowledge about the hydrological functioning of these impoundments and the biophysical controls on their water fluxes. Typically, there is one rainwater harvesting system every 1,000 ha within the cattle-grazed rangeland, that each collect only a tiny fraction of the rain falling in their contributory areas (Magliano *et al.* 2015c). Although rainwater harvesting systems make cattle production possible in the region, they are not considered efficient systems because of their perceived large water losses. During dry years, or at the end of the dry season, impoundments often run out of water generating serious problems for cattle ranchers. While local ranchers believe that water depletion in impoundments results from a combination of consumption by cattle and evaporation, the preliminary study of Magliano *et al.* (2015c) suggested that leakage through the impoundment floor may be an important water loss. Detailed understanding of the hydrological functioning of example impoundments is, therefore, a potential first step to improving the design and management of these rainwater harvesting systems in the Dry Chaco of Argentina and similar systems in other rangelands worldwide.

This study explored the hydrological functioning of two instrumented impoundments built to hold harvested rainwater in the Dry Chaco rangelands of Argentina (Figure 1). Two particular impoundments were selected for this first pioneering study because of the potential importance of the combined effects of cattle consumption of the impoundment water and the effects of trampling of the impoundment floor during cattle access for drinking. One impoundment ('cattle impoundment') was selected, as cattle accessed that impoundment to drink (Figure 1). The second impoundment did not have cattle access or water consumption (though it did have compacted tracks within its contributory area) and was selected as a reference or 'control' to permit the study of the effects of cattle presence/absence within an impoundment.

The first objective of the study was to quantify the storage dynamics of the two instrumented impoundments over the water year. The second objective was to estimate, for the first time: (1) the temporal dynamics of the additions to storage from infiltration-excess overland flow from the local rainfall, and (2) a decomposition of the losses from storage attributed separately to open water evaporation, cattle drinking and leakage through the impoundment floor. As the most critical attribute of the cattle-drinking impoundments is maintenance of storage for the longest period possible (i.e. security from water supply failure), the dynamic relationship between the unique synchronous rainfall and impoundment storage data were analysed using a systems modelling approach. This final objective being to quantify the residence time of a unit input of rainfall within the two impoundments (i.e. how long storage is maintained for standardised rainfall inputs), one with cattle consumption and trampling, one without.

METHODS

Study site

Extensive cattle ranching represents the most important economic activity of the Dry Chaco rangelands of Argentina. Drinking water for cattle is supplied by rainwater harvesting systems, while native grasses and woody species provide the forage (Aguilera 2003). This study was undertaken within a 20,000 ha farm located in the centre of the San Luis province of Argentina (33.5°S, 66.5°W; Figure 1) and was managed by Ser Beef S.A. Typical stocking rates

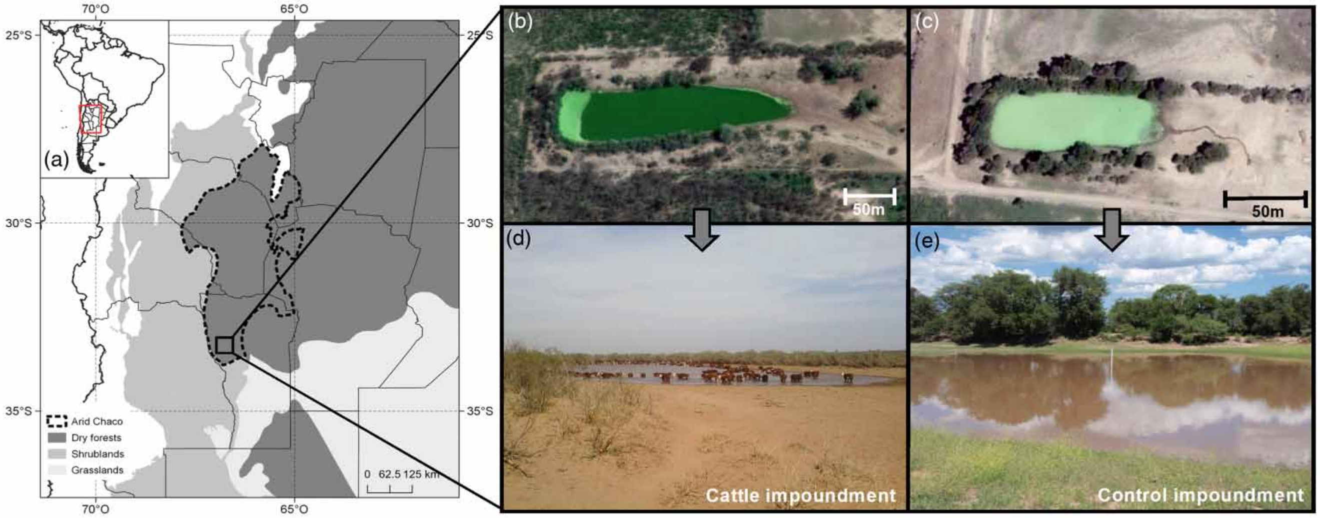

Figure 1 | Study site in central Argentina. (a) The map on the left shows the Dry Chaco rangelands (Arid Chaco, ~10 million of hectares), while (b) and (d) are images of the instrumented impoundment used for cattle water supply (cattle impoundment), and (c) and (e) are the control impoundment. Images (b) and (c) are publically available 'Quickbird' images from Google Earth, while the lead author took photographs (d) and (e).

were 0.15 calving units per ha (Ser Beef S.A. personal communication).

The vegetation is dominated by native dry woodlands with isolated stands of altered vegetation that include rainfed pastures of *Cenchrus ciliaris* and *Eragrostis curvula* and some localised irrigated plots of maize, sorghum and soybean (Marchesini *et al.* 2015; Steinaker *et al.* 2016). The native dry woodlands are dominated by two tree species: *Prosopis flexuosa* and *Aspidosperma quebracho-blanco*. The understorey includes several shrub species such as *Larrea divaricata* and *Senna aphylla*, and perennial grasses such as *Stipa eriostachya* and *Aristida mendocina* (García *et al.* 2017). The mean leaf area index of the dry woodland approaches 1 and mean incident radiation at the ground level is 47.5% (García *et al.* 2017).

The soils are well drained and derived from fine loessic sediments deposited throughout the Holocene with some alluvial reworking (Iriondo 1993; Tripaldi *et al.* 2013). Soils are Typic Torriorthents with 53% sand, 15% clay, and 1.4% organic matter in the top 10 cm of the profile (Peña Zubiate *et al.* 1998; Pennington *et al.* 2000). Topography is gentle with slopes of <1.5%. Saturated hydraulic conductivity values around 140 mm h^{-1} have been measured for the surface soil in nearby undisturbed, native dry woodlands, with dry bulk density and 'water holding capacity' values of approximately 1.2 g cm^{-3} and 20.6%, respectively (Magliano *et al.* 2017b). The regional water table is approximately 30 m deep at the study site (Ser Beef S.A. unpublished data).

The climate is semiarid with a long-term mean annual rainfall of only 429 ± 83 mm (mean and standard deviation), distributed in 40 ± 12 events per year (Magliano *et al.* 2015b). Rainfall has a strong seasonal pattern. Some 85% of annual rainfall occurs in the wet season of September–March. During the wet season, there are more rainfall events of larger size and so more likely to generate infiltration-excess overland flow. The mean annual potential evapotranspiration is approximately 1,500 mm $year^{-1}$ (New *et al.* 2002) and reaches maximum daily values of approximately 8.5 mm day^{-1} in the summer (Magliano *et al.* 2017a). The mean annual temperature is 17.8 °C. The hottest and coldest months have mean temperatures of 24.8 (January) and 10.3 °C (July), respectively. Some 38 ground frost events are observed each year, mostly in the cold dry season (New *et al.* 2002).

Field monitoring of control and cattle-affected impoundments

Imagery of the 'cattle impoundment' is given in Figure 1(b) and 1(d), and for the 'control impoundment' (with no cattle ingress) in Figure 1(c) and 1(e). At each impoundment, the water level was monitored using a data-logged pressure transducer (depth resolution ±2 mm; Hobo, Onset Corporation, Bourne, MA, USA). As the impoundments have a bowl shape, sensors were installed at the base of the deepest point, and the water level was recorded every 30 min. All monitoring was undertaken between 10th November 2010 and 4th January 2012, totalling 421 days of measurements. A detailed bathymetric survey of both impoundments was undertaken so that the daily-average water levels could be converted into values of daily water volume (Equations (1) and (2)) and daily water surface area (Equations (3) and (4)). Further details of the water volume calculations using an adapted fitting curve method applied to the high-resolution digital elevation model are presented in Magliano *et al.* (2015c). The derived level to volume relationships for the cattle and control impoundments are given in Equations (1) and (2), respectively:

$$V = 1335.5\,h^2 - 125.8\,h \tag{1}$$

$$V = 1033.9\,h^2 - 181.5\,h \tag{2}$$

where V is the water volume (m^3) and h is the water level (m), and level to water surface area relations are given in Equations (3) and (4), respectively:

$$S = 2586.7\,h \tag{3}$$

$$S = 1993.3\,h \tag{4}$$

where S is water surface (m^2) and h is water level (m)

Rainfall was measured with a tipping-bucket gauge installed 1 km from the impoundments (resolution = 0.1 mm per tip; Vantage Pro2 weather station, Davis Instruments, USA), and accumulated tips recorded every 30 min. The annual average rainfall recorded by the tipping-bucket gauge was checked against those data from a nearby storage rain gauge. Meteorological records of solar radiation, temperature, humidity and wind speed from the same Vantage Pro2 weather station were used to estimate open water evaporation using an adapted Penman method (following Allen *et al.* 1998).

Derivation of infiltration-excess inputs and evaporation, consumption and leakage outputs of the impoundments from the storage dynamics and associated data

Water loss from the two impoundments by the combined effect of open water evaporation, drainage through the impoundment floor and consumption by cattle, was derived on a daily time-step:

$$Y = (x_n - x_{n-1}),\ \text{where } (x_n - x_{n-1}) < 0 \tag{5}$$

where a negative Y is daily water loss ($\text{m}^3\ \text{day}^{-1}$), x is water volume at n day. In the case of $Y > 0$, this equates to very short episodes of recharge of the impoundment (m^3) by infiltration-excess overland flow from the surrounding 'rainwater harvesting' catchment.

Daily water loss was decomposed into estimates of the three component fluxes (evaporation, cattle consumption and drainage through the impoundment floor), using Equations (6)–(8), respectively:

$$y_e = x_1^* S,\ \text{where } Y < 0 \tag{6}$$

where y_e is daily estimate of the volume of water lost by evaporation from the impoundment (m^3), x_1 is daily evaporation depth estimate by the adapted Penman method of Allen *et al.* (1998; m) and S is water surface area of the impoundment (m^2):

$$y_c = x_2^* n,\ \text{where } Y < 0 \tag{7}$$

where y_c is daily cattle water consumption volume from the 'cattle impoundment' (m^3), x_2 is the daily rate of consumption estimated to be $0.05\ \text{m}^3$ per cow for dryland sites (Schlink *et al.* 2010) and n is the number of cattle accessing the 'cattle impoundment' each day (300 cows: Ser Beef S.A. personal communication). The cattle access the studied impoundment eight months per year; in this study, the access started on 15th February 2011 (Ser Beef S.A. personal communication). Consequently, the estimate of the drainage through the floor of the impoundment is the total water loss minus the evaporation and consumption:

$$y_i = Y - y_e - y_c,\ \text{where } Y < 0 \tag{8}$$

where y_i is daily volume of infiltration into the floor of the wetted area of the impoundment (m^3), Y is daily volume losses from the rate of change of water level (m^3), y_e is daily evaporation volume (m^3) and y_c is daily cattle consumed water volume (m^3).

The overall input–output water balance of each impoundment over the 421-day period, taking into account the infiltration-excess overland flow inputs of the rainwater harvesting system (m^3) and the losses (evaporation, cattle consumption and drainage through the impoundment floor, m^3), was then computed with Equation (9):

$$y = \sum a - \sum b \tag{9}$$

where y is the daily volume balance, a is an impoundment input and b is an impoundment loss. To explore the dynamics these daily values were expressed as a percentage of the maximum observed storage (6,140 and 4,102 m^3 for cattle and control impoundment, respectively).

Systems analysis of the input-storage dynamics of the impoundments

Rainwater harvesting is the dominant strategy for supplying drinking water to cattle in the Dry Chaco rangelands of Argentina. The main concern of ranchers is to have enough water at the end of the dry season, i.e. August (Figure 2(a)). Consequently, a key hydrological characteristic of the impoundments constructed for cattle water supply is how long a unit input of rainfall can be maintained in an impoundment.

To quantify how long storage can be maintained following a unit input of rainfall, a transfer-function approach has been used to identify the relationship between rainfall intensity and impoundment storage. The approach used was the

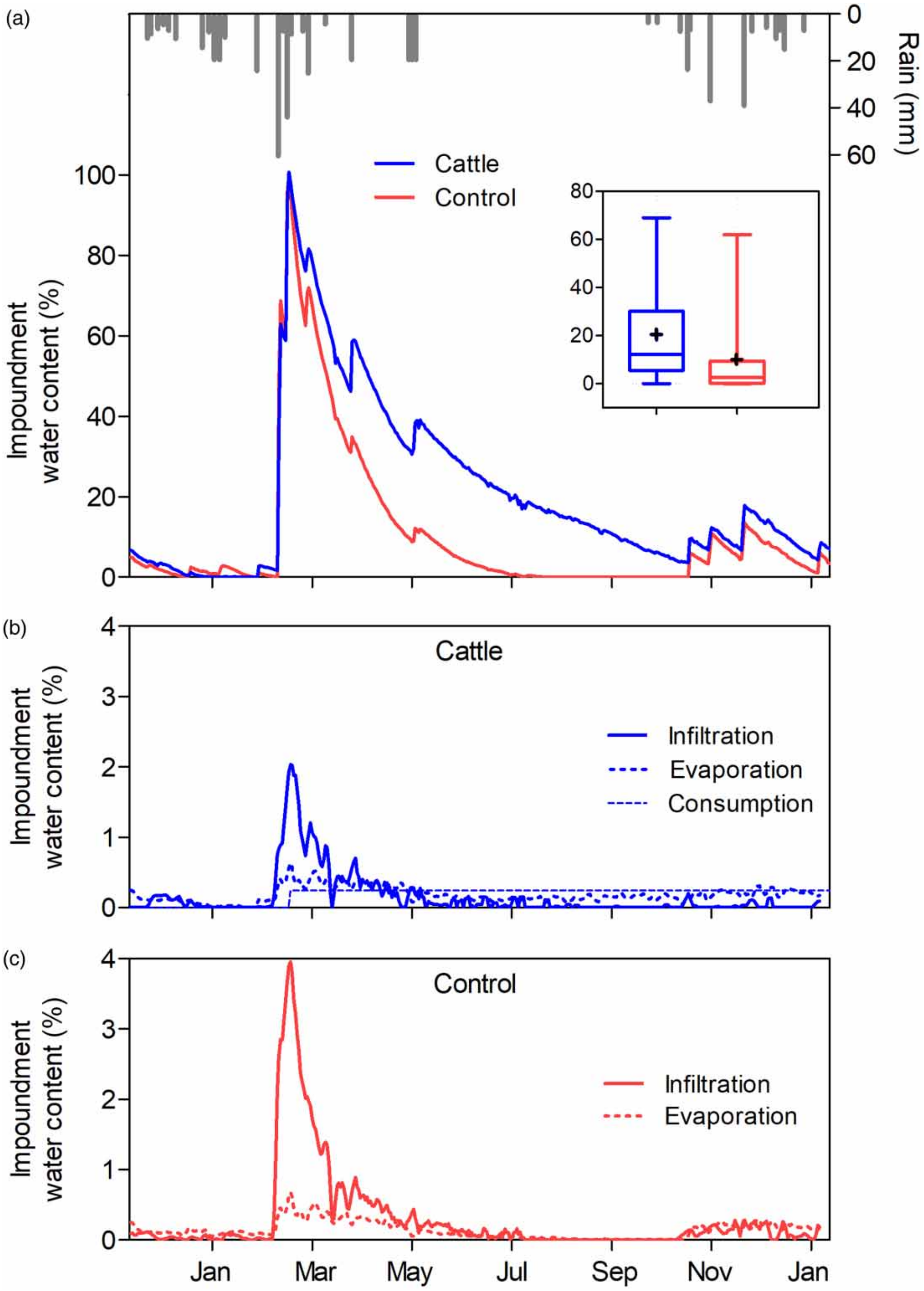

Figure 2 | Temporal dynamics of water content and derived losses for cattle and control impoundments, where: (a) water content dynamics, with the inset showing the distribution of the data; (b) dynamics of the derived estimates of evaporation, infiltration/leakage and consumption in the cattle impoundment; and (c) dynamics of the same variables for control impoundment.

Refined Instrumental Variable in Continuous-time (RIVC) algorithm of Young (2015) which is one of the algorithms that form the CAPTAIN Toolbox for Matlab™ (Taylor *et al.* 2007).

In summary, the RIVC algorithm implements an iterative instrumental variable method for estimation of general *Transfer Functions* that capture the dynamic relationship between an input (here rainfall, *R*) and an output variable (here impoundment water volume, V) that can be written as:

$$V = \frac{\beta}{s - \alpha} e^{-sT} R; \; s \sim \frac{d}{dt} \tag{10}$$

where V is the impoundment water volume ($\mathrm{m}^3\ \mathrm{day}^{-1}$), R is the rainfall ($\mathrm{mm\ day}^{-1}$), T is the pure time delay between R and an initial V response, where present (given in number of day intervals), α is the parameter capturing the rate of impoundment depletion or residence time of response (day^{-1}), β is the parameter capturing the magnitude of volume gain ($\mathrm{m}^3\ V$, $\mathrm{mm}^{-1}\ R$), t is time in 1 day periods, and s is the Laplace operator. Full details of this method are given in Young (2015).

Physical interpretation of the behaviour is made after first calculating the dynamic response characteristics (DRCs) of the observed dynamics derived from transfer function parameters α and β. These DRCs include the time constant (TC) or residence time of response (here residence time of the storage following a unit input of rainfall):

$$TC = \frac{\Delta t}{\alpha} \tag{11}$$

where Δt is the time-step (days).

RESULTS AND DISCUSSION

Analysis of infiltration-excess overland-flow inputs to each impoundment

The accumulated infiltration-excess overland flow input to each impoundment (from the surrounding 'rainwater harvesting' catchment) over the 421 days of measurements was 10,690 and 6,630 m^3 for the cattle and control impoundments, respectively (Table 1). This is 1.7 and 1.6 times the maximum water storage capacity of the respective impoundments.

The inputs to the two impoundments were characterized by very short, discrete events of infiltration-excess overland flow, contrasting with the continuous losses to evaporation, leakage and cattle drinking (Figure 2(a)). The 421 days of the study period received 616.5 mm of rainfall. This was distributed in daily events ranging in size from 0.1 to 60 $\mathrm{mm\ day}^{-1}$. The largest 10% of rainfall events accounted for 42.9% of total rainfall amount, reflecting the typical asymmetric distribution of rainfall in drylands (Knapp *et al.* 2015; Magliano *et al.* 2015b).

Table 1 | Total water inflows by infiltration-excess overland flow ('water harvested'), total water losses and their components (including percent of total loss) of open water evaporation from the impoundment, leakage through the floor of the impoundment and direct consumption of impoundment water by cattle

	Cattle		**Control**	
	m³	**%**	**m³**	**%**
Water harvested	10,690		6,630	
Water losses	10,673		6,835	
Storage change	17		–205	
Evaporation	4,666	43	2,392	35
Basal pond leakage	1,549	15	4,443	65
Consumption	4,458	42		

The smaller rainfall events ($<20\ \mathrm{mm\ day}^{-1}$) seemed to generate much less infiltration-excess overland flow and so an increase in storage compared to the larger events ($>30\ \mathrm{mm\ day}^{-1}$). Indeed both impoundments reached their maximum storage capacity only once in the study period, after a 60 mm rainfall event that was swiftly followed by a 45 mm event. Both impoundments were completely filled once on 13th February 2011. On this day, the maximum water depth was 2.19 m in the cattle impoundment, while water volume and water surface area were 6,140 m^3 and 6,134 m^2, respectively. In the control impoundment, the maximum water depth was 2.08 m, maximum water volume was 4,102 m^3 and maximum water surface area was 4,543 m^2.

To demonstrate the role of the event characteristics on preferential impoundment filling, the overland inflows into the impoundments were explored at a higher temporal resolution (30 min) during two example rainfall events of similar total event size but different short term intensity characteristics (Figure 3). In the cattle impoundment, the high-intensity event generated five times more overland flow than the low-intensity longer duration event (3,742 vs. 710 m^3); and 10 times more in the control impoundment (2,937 vs. 281 m^3; Figure 3).

Examining the full record of daily events, the cattle impoundment had 16 discrete input events while the control

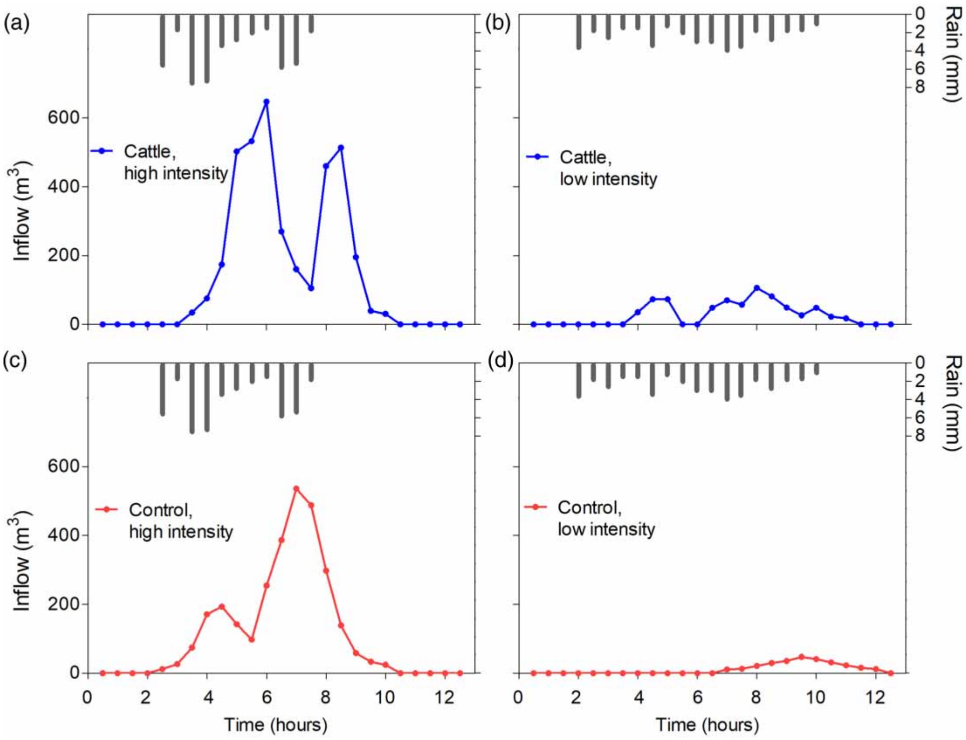

Figure 3 | Inflows recorded every 30 min in the cattle- (a) and (b) and control- (c) and (d) impoundments during example high-intensity (a) and (c) and low-intensity (b) and (d) rainfall events. High-intensity rainfall corresponds to a 45 mm event size with a weighted average intensity of 5.3 mm h^{-1}. Low-intensity rainfall corresponds to a 40 mm event size with a weighted average intensity of 2.8 mm h^{-1}.

had 13. Critically, the minimum daily rainfall event able to generate an infiltration-excess overland flow input to an impoundment was only 4 mm day^{-1} in the cattle impoundment and a larger 20 mm day^{-1} in the control. These observations may indicate that the surface of the catchment draining to the cattle impoundment was naturally less permeable than that of the control impoundment or that the cattle in the former catchment have more extensively compacted the ground enhancing the proportion of infiltration-excess overland flow relative to catchment-wide infiltration. This is consistent with the observations of long compacted cattle trails directed towards drinking impoundments seen in other regions (Ganskopp *et al.* 2000; Ganskopp & Bohnert 2009; Chillo *et al.* 2015).

Analysis of consumption, evaporation and leakage losses from each impoundment

The analysis of the storage dynamics showed that total water losses from the impoundments to all processes over the 421-day monitoring period were 10,673 and 6,835 m^3 from the cattle and control impoundments, respectively (Table 1). The difference between impoundment storage at the start and end of the 421-day period, for both impoundments, was negligible. Consequently, application of Equations (6)–(8) indicates that consumption by cattle represents 42% of the water input to the impoundment where cattle walk inside the impoundment to drink, with a similar amount lost to evaporation (43%), plus 15% lost through infiltration ('leakage') into the impoundment floor. In marked contrast, infiltration through the impoundment floor of the impoundment with no cattle access (or consumption) amounted to 65% of the water entering the impoundment, with a further 35% lost to evaporation.

Depletion of impoundment storage due to the combined losses (expressed by reductions in impoundment storage within Figure 2(a)), followed a clear exponential relationship ($R^2 = 0.82$ and 0.96 for cattle and control impoundment, respectively; Figure 4). The control

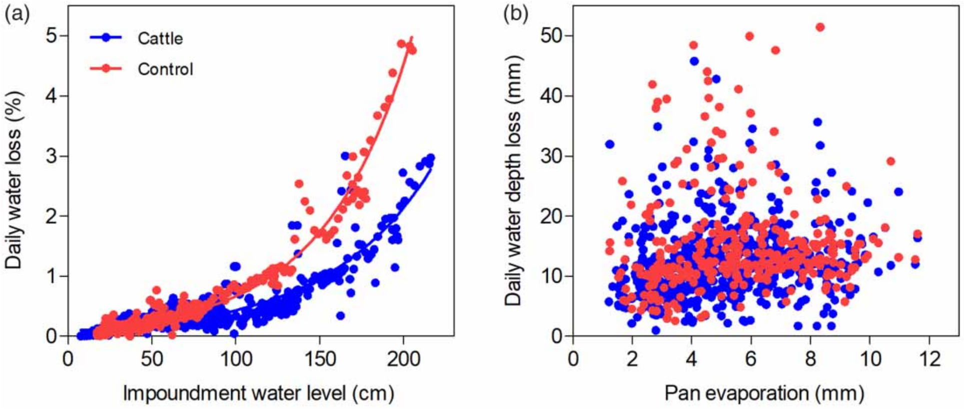

Figure 4 | Relationship between daily water loss (by all processes affecting that impoundment), expressed as a percentage of impoundments maximum storage capacity versus water level of both impoundments.

impoundment lost its water at a higher rate. For example, when the impoundments were full of water, daily losses were 4–5 and 2–3% of stored volume, for the control and cattle impoundments, respectively. Expressed differently, the cattle impoundment showed smaller variations in storage that were maintained closer to maximum storage on average (i.e. 20.4 ± 50.9% coefficient of variation, compared to 9.8 ± 102.0% for the control impoundment; Figure 2(a) inset).

At both impoundments the estimate of the evaporation was at its highest when the storage was at its greatest (Figure 2(a) and 2(b)), as the lateral extent of the impoundment surface was at its greatest at these times. Similarly infiltration (or 'leakage') into the impoundment floor was greatest at times of deepest water, as these were times of greatest hydraulic head driving the water into the impoundment floor. The rate of water loss into the soil below the control impoundment (relative to observed max storage) was, however, twice that beneath the impoundment where cattle were allowed to access. Indeed, 62% of the storage in the control impoundment was lost by infiltration in just one month (i.e. 13th February–15th March 2011). Either the impoundment floor of the 'cattle impoundment' has naturally less permeable soils, or trampling of the impoundment floor by cattle when they access to drink has reduced the permeability of the impoundment floor (so reducing leakage). Indeed wet soils beneath impoundments are likely to be particularly sensitive to cattle trampling (Belsky *et al.* 1999; Lebron *et al.* 2007; Fernández *et al.* 2015; Magliano *et al.* 2017b).

Systems (transfer function) modelling of input-storage dynamics

Application of the RIVC identification algorithm to the rainfall to storage dynamics of the two impoundments was shown to be able to capture more than 90% of the variance in the daily impoundment volume, m^3 (Figure 5; Table 2), thereby permitting comparison of the derived response characteristics between the two impoundments. Purely linear, first-order transfer function model parameters (see Equation (10)) were first identified for the cattle impoundment and a Nash–Sutcliffe simulation efficiency (R_t^2) of 0.875 was observed. The generation of infiltration-excess overland flow is sensitive to the wetness of the surface of the catchment. This may be represented by a single 'memory term' based on the rainfall history. Within this study, the memory term of the 'Bedford-Ouse Sub-Model', BOSM (see Equations (5) and (6) in (Chappell *et al.* 2006) was applied to the rainfall data, with R_{eff} replacing R in Equation (10). By including this one additional term, simulation efficiency increased to 0.945 (Table 2). It is worth mentioning that adding additional parameters can introduce uncertainty to simulation where the information content of the observations is insufficient to warrant the addition of further parameters. This was evaluated with the calculation of the Young Information Criterion, YIC (Young 2015). In the case of the cattle-affected impoundment, the addition of the single BOSM term shifted the value of the YIC performance measure from −8.584 to −10.391 (Table 2). A more negative number indicates

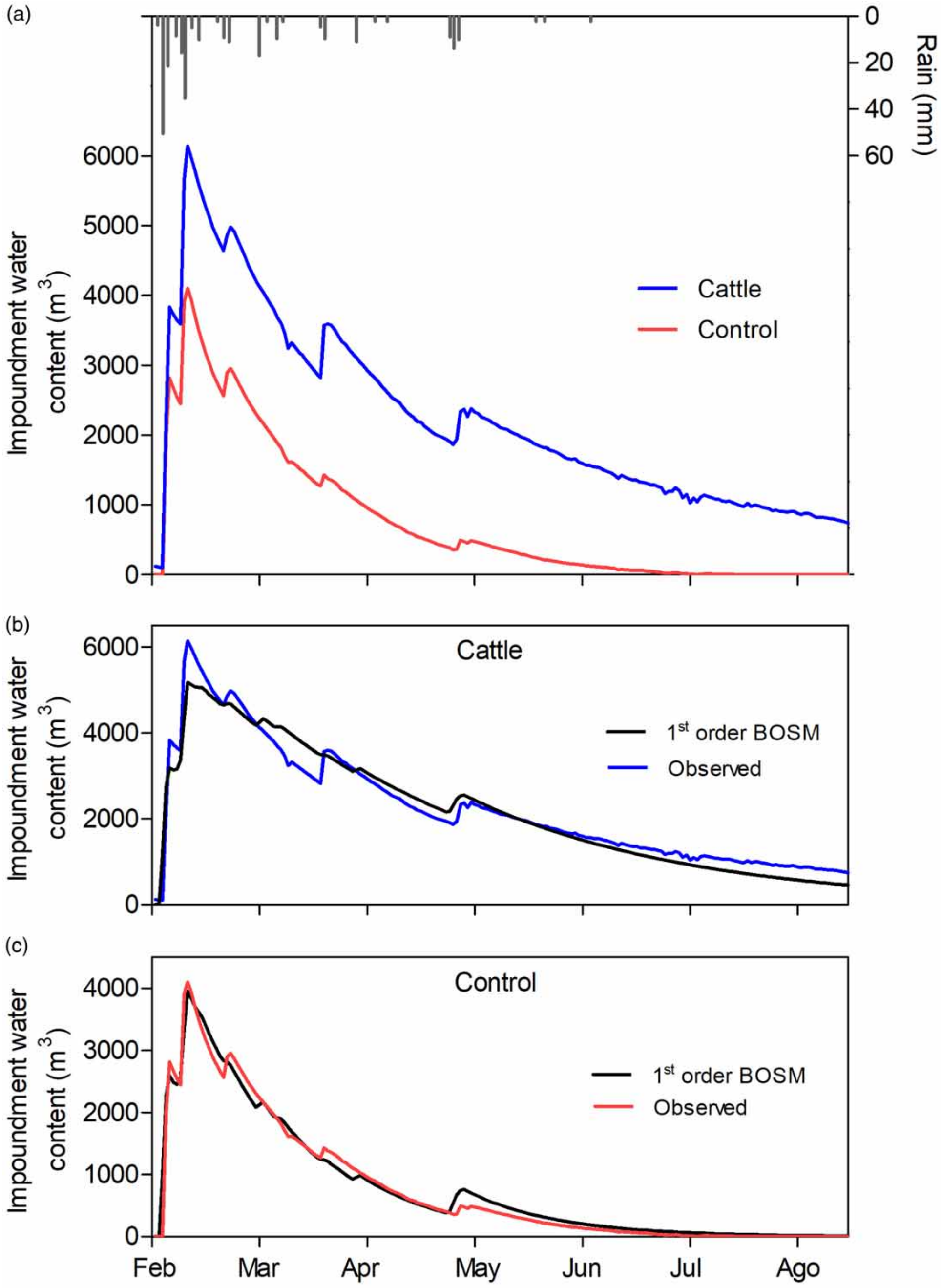

Figure 5 | Observed rainfall and impoundment volume: (a) together with the RIVC-simulated cattle- (b) and control- (c) impoundment volume.

that the use of a more slightly complex structure (i.e. adding one additional term) is warranted by the dynamics in the observed data.

The derived residence time of the response of the storage for a unit input of rainfall to the catchment (Equation (11)) was 62 days for the impoundment affected by cattle access. In contrast, the residence time for the storage in control impoundment was only 25 days (Figure 5(c) and Table 2). Thus, despite the consumption of water by cattle drinking, the less permeable bed of the cattle-affected impoundment retained the water in the impoundment for longer. This greater retention may have been an unintended

Table 2 | The identified transfer function parameters of BOSM nonlinearity term and pure time delay with the derived dynamic response characteristic of the time constant or residence time of response for each impoundment, together with measures of simulation performance (R_t^2, YIC)

	Cattle	Control
BOSM rainfall memory (days)	2	2
Pure time delay, τ (days)	0	0
Measures of simulation performance		
R_t^2	0.94469	0.98272
YIC	−10.3911	−11.888
Time constant or residence time of response (days)	62.1183	25.0948

The identification routine of the RIVC (Refined Instrumental Variable in Continuous-time) algorithm of Young (2015) was applied to the 421 days of daily rainfall and impoundment volume observations.

beneficial effect of the cattle trampling the floor of the impoundment when accessing to drink.

CONCLUSIONS

Rainwater harvesting remains essential for cattle production in the Dry Chaco rangelands of Argentina. This pioneering study into the hydrological functioning of a typical harvesting-impoundment system used for watering cattle against a similar physical system, except for cattle exclusion from the impoundment, produced the following key conclusions:

- The impoundment functioning (cattle-affected and control) is characterised by very short filling events (from infrequent rainfall events) with continuous losses of storage to evaporation and leakage (and also consumption in the cattle-affected impoundment);
- Most inflow is attributed to rainfall events of greater short-term intensity, due to the greater generation of infiltration-excess overland flow rather than infiltration;
- Some 43% of the storage was lost to open water evaporation in the cattle affected impoundment, and a similar 35% from the control impoundment;
- Using the value of 0.05 m^3 per cow multiplied by 300 cows for water consumption from within the cattle-affected impoundment, this left only 15% of the water balance to loss by leakage through the impoundment floor. In considerable contrast, leakage through the impoundment floor amounted to 65% of the stored water in the impoundment without cattle. This greater leakage may be attributed tentatively to the absence of the beneficial effect of cattle trampling reducing the saturated hydraulic conductivity of the impoundment floor;
- Calculation of the water balance components involves uncertainty, particularly the estimates of cattle water consumption and open water evaporation, with the resultant impact on the estimate of impoundment leakage. Future studies on the hydrological functioning of these rainwater harvesting and storage systems should focus on quantifying and reducing the uncertainties in these three key variables;
- The systems modelling allowed quantification of the residence time of storage to unit inputs of rainfall, showing that the impoundment used for cattle drinking counterintuitively maintained storage longer (62 days residence time) than that of the impoundment without cattle ingress (25 days residence time). The beneficial effect of cattle trampling on the saturated impoundment floor to reducing leakage being a plausible first interpretation.

If further studies (with greater constraints on uncertainty in comparison to this pioneering study) similarly show the beneficial effect of cattle trampling on reducing leakage through the impoundment floor, this would have management implications for cattle ranchers in the Dry Chaco rangelands of Argentina. Cattle acting unconsciously as beneficial 'ecosystem engineers' in reducing impoundment leakage, in addition to their acknowledged impact of enhancing impoundment inflows by trampling effects in the contributory catchment, is a finding that cattle ranchers should be aware of. Semi-arid regions across the world are increasingly affected by livestock grazing (Schlesinger *et al.* 1990; Reynolds *et al.* 2007). It is critical that hydrologists undertake experimental studies to quantify both beneficial and negative impacts of these grazers on the sustainability of the natural environment and the food producing systems.

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