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Analysis of channel transmission losses in a dryland river reach in northeastern Brazil using stream flow series, groundwater level series and multi-temporal satellite data

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Abstract:

Scarcity of hydrological data, especially stream flow discharge and groundwater level series, restricts the understanding of channel transmission losses (TL) in drylands. Furthermore, the lack of information on spatial river dynamics encompasses high uncertainty on TL' analysis in large rivers. The objective of this study was to combine the information from stream flow and groundwater level series with multi-temporal satellite data to derive a hydrological concept of TL for a reach of the Jaguaribe river (JRR) in semiarid northeastern Brazil. Based on this analysis, we proposed strategies for its modelling and simulation. TL take place in an alluvium, where river and groundwater can be considered to be hydraulically connected. Most losses certainly infiltrated only through streambed and banks and not through the flood plains, as could be shown by satellite image analysis. TL events, whose input river flows were smaller than a threshold, did not reach the outlet of JRR. TL events, whose input flows were higher than this threshold, reached the outlet losing on average 30% of their input. During the dry seasons (DS) and at the beginning of rainy seasons (DS/BRS), no river flow is expected for pre-events and events have vertical infiltration into the alluvium. At the middle and the end of the rainy seasons (MRS/ERS), river flow sustained by base flow occurs before/after events and lateral infiltration into the alluvium plays a major role. Thus, the JRR shifts from being a losing river at DS/BRS to become a losing/gaining (mostly losing) river at MRS/ERS. A model can be a coupling of river and groundwater flow models linked by a leakage concept-based approach. This strategy has been mostly undertaken in humid and temperate catchments and not in semi-arid ones. Also, an event-based empirical approach may be applied to input river flow to estimate roughly TL.

KEY WORDS channel transmission losses; multi-temporal RapidEye satellite data; semiarid hydrology; northeastern Brazil; dryland rivers; river-aquifer interaction

INTRODUCTION

Channel transmission losses are a key factor for water and environmental planning and management in dryland environments, since they reduce not only surface flow volume, but also peak discharges; support riparian vegetation; and are a major source of potential groundwater recharge (Sharma and Murthy, 1994; Sharma *et al.*, 1994; Lange, 2005; Dagès *et al.*, 2008; Wheater, 2008; Morin *et al.*, 2009). Their dynamics have shown high nonlinearity in relation to stream flow magnitude:

a) Initial infiltration losses were smaller than during the main phase of the flood in a flash flood experiment in the southern Negev Desert, Israel (Lange *et al.*, 1998).

b) Small to medium floods could travel considerable distances without substantial losses, whereas significant transmission losses occurred during high runoff peaks in a 150 km channel reach of the Kuiseb River, Namibia Desert. High runoff peaks were significantly diminished after the runoff had exceeded a certain threshold level (Lange, 2005).

c) Small floods did not usually traverse the full distance between stream gauges, whereas larger flows transmitted to the outlet about 20-50% of their discharge in a 420 km channel reach of the Cooper Creel River in Australia. Then, at a certain threshold level of input river flow, transmission losses increased again and flows transmitted to the outlet were about 10-20% of their discharge. Only during the largest floods did river flow transmission efficiency increase sharply (Knighton and Nanson, 1994).

For large river systems, that nonlinearity might be explained mainly by:

a) Pools, subsidiary channels and/or floodplain areas which act as sink areas of flows, but once they become fully saturated, the most direct floodways become fully active and river flow transmission efficiency increases (Knighton and Nanson, 1994; Lange, 2005)

b) A clogging layer within or on the alluvial surface, which can act as a seal that is disrupted at higher discharge (Lange, 2005). Indeed, stratified alluviums with hydraulic conductivity heterogeneity were reported from point infiltration experiments (Parissopoulos and Wheater, 1992) and local stratigraphies in dryland riverbeds (e.g. Lange, 2005).

Also, the subsurface water redistribution in the underlying alluvium may influence the infiltration rates from river to aquifer. The underlying alluvium saturation can be driven by local, intermediate or regional groundwater flow systems (Sophocleous, 2002), in which potential abstractions are through transpiration by (near-)river channel vegetation (Goodrich *et al.*, 2004; Blasch *et al.*, 2004) and groundwater pumping (Shentsis, 2003; Shentsis and Rosenthal, 2003).

Channel transmission losses take place in hydraulically connected or disconnected groundwater-river systems (Sophocleous, 2002). When hydraulically connected, the gradient between river and groundwater plays a major role in transmission losses, indicating whether they occur or not (see e.g. Lima *et al.*, 2007).

Moreover, a fundamental physical principle which explains higher transmission losses at higher stream discharge is the increase of infiltration due to higher hydraulic head at the surface. This assumption was taken in account for channel transmission losses modelling by Abdulrazzak and Morel-Seytoux (1983), Freyberg (1983), Illangasekare and Morel-Seytoux (1984), El-Hames and Richards (1998) and Xie and Yuan (2010).

However, the findings of Dahan *et al.* (2008) in the Kuiseb river, Nambia, suggested that the microlayering of the sandy alluvial sediments at the top of the vadose zone regulates the flux process through almost constant infiltration rates. This disagrees with the hypothesis of a flood-stage-based surface-groundwater flux process. Therefore, large transmission losses during high flood stages may be due to long duration of high floods (Dahan *et al.*, 2008).

Scarcity of hydrological data, especially simultaneous stream flow discharge and groundwater level series, in dryland environments restricts the understanding of transmission losses processes. Furthermore, the lack of information on spatial river dynamics between stream gauges encompasses high uncertainty on transmission losses' analysis in large rivers.

In this paper, we address these problems by investigating channel transmission losses in a 60-km reach of the Jaguaribe river in semiarid northeastern Brazil. The river reach is located upstream of the 1·940 $10^6 m^3$ Orós reservoir (Figure 1), one of the most important water resource for the whole Jaguaribe basin.

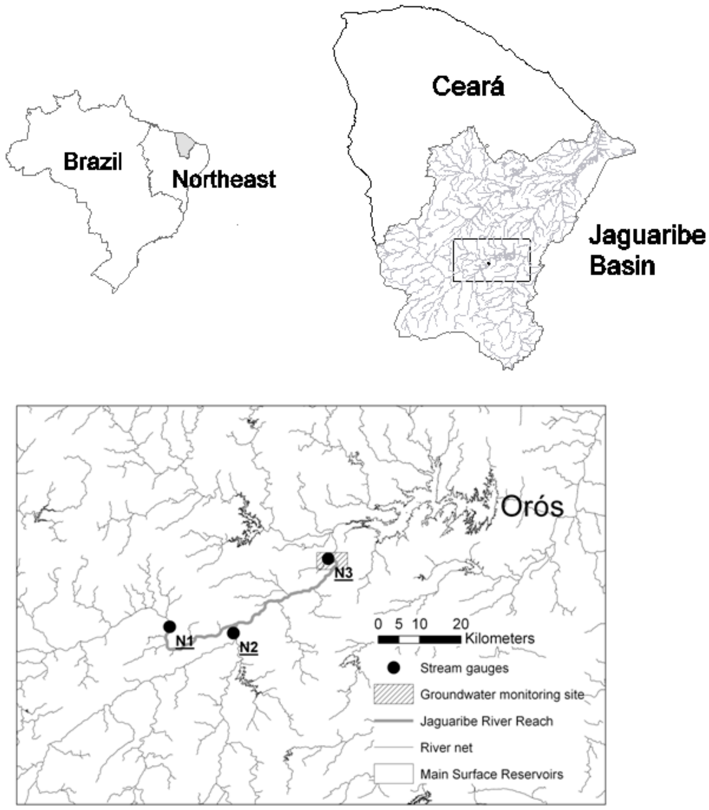

Figure 1. Location of the Jaguaribe river reach at study in relation to the Orós reservoir.

The general objective of this study is to combine the information from stream flow and groundwater level series with multi-temporal satellite data to derive a hydrological concept of channel transmission losses for a large Jaguaribe river reach. Based on this analysis, we propose strategies for its hydrological modelling and simulation.

Using the stream flow series, we intend to a) quantify the event-based channel transmission losses and their impact on the input flow volume and peak, b) verify the relationship between transmission losses and input flow magnitude, and c) indentify the existence of runoff thresholds, which separate hydrological behaviours.

Analyzing the groundwater level series, we intend to a) determine whether the river-groundwater system is hydraulically connected or not, b) verify whether the recession limb of the outlet is driven not only by the upstream boundary conditions, but also by the return flow originated from the previous transmission losses.

Assessment of channel transmission losses are traditionally carried out by stream flow water balance and comparison between stream flow and groundwater levels, but satellite data have proved to be a valuable source to improve understanding of surface hydrological processes (van Dijk and Renzullo, 2011). They are particularly well suited in large remote catchments with restricted accessibility and therefore sparse hydrological measurements (Kite and Pietroniro, 2000). Satellite observations have been widely used for monitoring the extent of water bodies, e.g. in the context of flood monitoring, and mapping hydrological state variables, such as surface temperature, soil moisture and snow cover, to estimate hydrological fluxes, such as evapotranspiration and runoff (van Dijk and Renzullo, 2011; Schmugge *et al.*, 2002). So far satellite observations have, however, hardly ever been used in the context of transmission losses.

For that purpose, particular satellite systems with a frequent coverage may provide valuable information on seasonal, annual and long-term changes of surface water present in the riverbed or floodplain and of water surface connectivity along the river and its tributaries (see e.g. Costelloe et al, 2006). Water surface mapping and monitoring using optical satellite data are based on the spectral characteristics of water in the near infrared and visual region as compared to soils and vegetation.

The main scientific questions related to the use of satellite-based remote sensing data in this research are:

a) Is the river confined within the streambed and banks or did it flow over the floodplain during flood events?

b) Has there been any indication of spatial variability in transmission losses in JRR?

c) Even when the stream gauges register non-flow, is surface water observable in the river reach?

STUDY AREA

The Jaguaribe river is 610 km long and the largest intermittent river in Brazil. Its basin covers an area of 76 thousand km^2 and is located within the institutional borders of the State of Ceará in the semiarid northeastern Brazil (Figure 1). The Orós reservoir, the second largest surface reservoir of the State of Ceará, is situated about 11 km downstream of the Jaguaribe river reach (JRR) under study (Figure 1).

The Jaguaribe river basin's hydrology is determined by an annual cycle of rainy and dry seasons, which are mostly driven mainly by the position of the Intertropical Convergence Zone and secondarily by cold fronts from the South Atlantic (Xavier, 2001; Werner and Gerstengarbe, 2003). The rainy season lasts up to six months (December-May) on average.

The high water deficit between rainy and dry seasons, about 1 m/yr of rainfall and 2·2 m/yr of potential evaporation, together with the scarce, salty and spatially concentrated groundwater resources have led to the construction boom of many surface reservoirs during the last century (there is about one on-river reservoir every 6 km^2: Malveira *et al.* (accepted). Furthermore, the large surface reservoirs have transformed about 600 km of river network into perennial waterways in the Jaguaribe river basin.

The Jaguaribe river reach (JRR), the focus of this research, is 60-km long and controlled by two upstream stream gauges (N1 and N2) and one downstream stream gauge (N3) (Figure 2). These two upstream stream gauges control a catchment area of 20 thousand km^2 of the Jaguaribe basin. The additional drainage area between the upstream gauges and the downstream gauge is 1000 km^2. This area contains about 130 surface reservoirs. Water has been released from upstream surface reservoirs into JRR since the dry season of 2007.

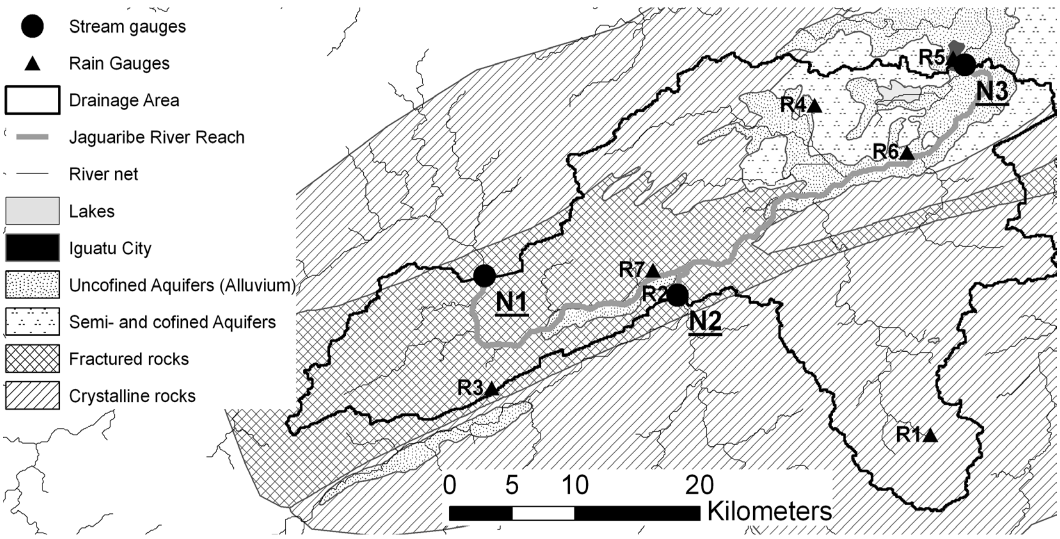

Figure 2. Jaguaribe river reach (JRR) under study. The description of the hydrogeology was adapted from IBGE (2003).

Water consumption for agricultural purposes in the JRR is mainly supplied by tubular wells in an alluvium, which is characterized by unconfined aquifers, contiguous to the Jaguaribe river main stream (Figure 2). This alluvial groundwater extraction occurs predominantly during the dry season, whereas the continuous domestic supply for major towns and villages, including Iguatu City, is mainly provided by surface reservoirs or deep groundwater. This alluvium has a maximum thickness of 25 m with high permeability and overlays fractured rocks (IBGE, 2003). Its stratigraphy is composed of layers of fine and coarse sand, gravel and clay (IBGE, 2003). Moreover, the Orós reservoir is located over this same large alluvium-system (IBGE, 2003).

MATERIAL AND METHODS

Stream flow series

The Brazilian Geological Service (CPRM) has monitored the three stream gauges (N1, 2 and 3) in the JRR, measuring daily water level by rulers installed at the river sections and bimonthly discharges. The time series data are made available by the Brazilian Water Agency (ANA), see http://www.hidroweb.ana.gov.br. Water levels at the all three gauges have been measured simultaneously since 2001.

We used CPRM's flow discharge measurements to construct the rating curves. Then, we calculated an event-based water balance between input stream flow (N1 and 2) and output stream flow (N3), assuming the wave travel time from N1 and N2 to N3 equal to two days and one day, respectively. These travel times were estimated empirically from the differences between the days of peak flows at the stream gauges. We assumed that an event ends if another one begins at the end of its recession limb or if the stream flow ceased completely.

Furthermore, a transmission losses rate *TL* ($10^6m^3/10^6m^3$) was calculated for every event

$$TL = \frac{Output - Input}{Input} \quad (1)$$

where *Output* (10^6m^3) is the flow volume of the N3 stream gauge and *Input* (10^6m^3) is the sum of flow volumes of the N1 and 2 stream gauges. We described every event according to *TL* as follow

a) if $TL \approx -1$, then transmission losses were equal to the sum of the inflow from the upstream gauges (N1 and 2) and from the drainage area among the stream gauges. When floods occur during the dry season the inflow from the drainage area between the stream gauges can be neglected, because no significant rainfall over the drainage area controlled by the gauges has been registered whatsoever;

b) if $-1<TL<0$, then transmission losses were relevant and reduced the input flow from the the upstream gauges (N1 and 2) and from the drainage area among the stream gauges.

c) if $TL \approx 0$, then transmission losses were compensated by inflow from the drainage area among the stream gauges;

d) if $TL>0$, then inflow from drainage area among the stream gauges was greater than transmission losses.

Moreover, rainfall time series of seven rain gauges within the JRR, which are monitored daily by the Meteorological and Water Resources Foundation of the State of Ceará (FUNCEME) (see Figure 2), were also taken into account to verify the possible influence of the runoff generated from the drainage area between the stream gauges on the JRR's water balance (items c) and d) mentioned above).

In order to assess the channel transmission losses relating to the seasonal variation, the events have also been classified according to their seasonality based on the monthly river flow frequency through the years in the JRR. The dry season starts in July and lasts until January, the beginning of the rainy season from February to March, the middle of the rainy season from March to May and the end of the rainy season from May to July.

Previous investigation of the inflow from the drainage area among the stream gauges

The drainage area among the gauges is about 20 times less than the area which the upper gauges drain. Moreover, it contains about 130 surface reservoirs on the river network. However, the inflow from this drainage area (IDA) may influence the channel transmission losses in the JRR for medium and large events during the rainy season. If this hypothesis cannot be neglected, Eq. (1) will underestimate the channel transmission losses and, consequently, Eq. (1) alone should not be used for the investigation of the channel transmission losses for the case $-1<TL<0$.

To test this hypothesis, one may model ungauged catchments with a high density of small reservoirs (more than 1 reservoir/ 10 km^2) and low density of rain gauges (1 rain gauge/ 140 km^2), which needs large efforts on a) landscape data sampling, including the analysis of satellite data, b) new monitoring and data analysis frameworks for rainfall estimation and c) surface hydrological modelling itself. The WASA model, which is particularly well adjusted for semi-arid hydrology, has been successfully applied to runoff forecasting for large semi-arid catchments in the State of Ceará (Guentner and Bronstert, 2004; Guentner *et al.*, 2004). However, this model cannot reproduce well the river flow conditions at the end of the dry season and at the beginning of the rainy season, because channel transmission losses are not yet accounted for. Thus, a channel flow routine capable simulating transmission losses should be developed for the WASA model as well.

Such work, which may be the most suitable scientifically, is far beyond the scope of this research. Therefore, we tried in this section to estimate the order of magnitude of IDA using a simplified method, which sounds empirically.

First, we calculated the runoff coefficients of the drainage area among the gauges for the events, which belonged to the case *TL*>0 (see Table II), assuming IDA equal to the difference between the flow of the N3 stream gauge and the sum of the flow of the N1 and N2 stream gauges. The average rainfall of the events was estimated from the rain gauges within the JRR (Figure 2). The runoff coefficient was 4% on average. Cadier (1996) found an annual runoff coefficient of about 6% for a catchment with similar geo-hydro-climatic controls and reservoirs' density in the Jaguaribe river.

Then, using the estimated runoff coefficient we calculated IDA for every event, which was valid for the case -1<*TL*<0 (see Table II). We found that 3 of the 10 events (4, 13 and 26 in Table II) had IDA greater than 20% of the input flow of the N1 and N2 stream gauges. This result did not allow an investigation of the transmission losses of these events using only Eq. (1). On the other hand, the other events had on average IDA equal to 4% of the input flow of the upper gauges, which permitted the assumption that IDA can be neglected for these events and, consequently, the use of Eq. (1) alone for the estimation of their channel transmission losses.

The assessment of the effects of the surface water on the small events, which transmission losses were compensated by or smaller than the IDA, using the aforementioned simplified method would inevitably compromise a lot of uncertainties and was not undertaken.

Groundwater level series

We have monitored the water level of three tubular wells (W1, W2 and W3) on a daily basis (see: groundwater monitoring site in Figure 1). Figure 3 details the location of the N3 stream gauge and the nearby monitoring tubular wells. An approximated alluvial stratigraphy (Carneiro, 1993) of the site where these gauges are located is shown in Table I. Groundwater level in these wells has been measured since April 2010.

Figure 3. Location of the N3 stream gauge and the monitoring tubular wells (W1, W2 and W3) on August 18th 2007 (source: Google Earth).

Table I. Approximated alluvial stratigraphy, where the N3 stream gauge and the monitoring tubular wells are located (adapted from Carneiro, 1993).

Depth (m)	Texture
0 - 1	Loam
1 - 3	Loamy sand
3 - 9	Fine to coarse sand
9 - 29	Coarse gravel and very coarse sand

We compared the groundwater level series a) to the water level series of the N3 stream gauge during the rainy season of 2010 and b) to the stream flow series of the N1 and N2 stream gauges during dry season of 2010, when no flow was registered in the N3 stream gauge. In addition, the groundwater level in JRR (W1, W2 and W3) and the water level of the downstream Orós reservoir have also been compared in order to assess eventual groundwater discharge to this surface reservoir. The water level of the Orós reservoir is monitored daily by the Water Resources Agency of the State of Ceará (COGERH).

Multi-temporal satellite data

Multi-temporal satellite data were used to assess the spatial river dynamics between stream gauges. For this task, we chose the RapidEye system, which includes a constellation of five optical satellites and therefore allows a frequent coverage that is particularly important in areas such as our study area that are often covered by clouds. RapidEye collects large-area image data with 5 m spatial resolution in five bands (blue, green, red, red edge and NIR) on a daily basis (Rapideye, 2010).

Multi-temporal RapidEye data were acquired a) in 2009 during the dry season, i.e. non-flow registration by stream gauges, b) on April 20th 2010, exactly one day after the peak flow during the rainy season of that year, and c) on May 18th 2010 during the flow recession limb.

The satellite data were atmospherically corrected using *ATCOR3* in ERDAS Image 2010 to correct the effect of different illumination conditions due to varying acquisition dates and the terrain (see http://www.geosystems.de/atcor/). After the atmospheric correction, satellite image mosaics were generated using *Mosaic pro* in ERDAS Image 2010 to get a consistent image data set for each sampling period for further analysis.

We also delineated the streambed region of JRR based on the satellite image mosaic of 2009, which was acquired during non-flow conditions. Furthermore, we mapped the water surface extent within JRR based on the ratio between red and near infrared bands of the satellite image mosaics acquired on April 20th and on May 18th 2010.

RESULTS

Stream flow series

Figures 4 and 5 show the cross-sections and the rating curves of the stream gauges at JRR, respectively, wherein water level is the difference between stream flow and streambed levels according to the rulers at the river sections. The number of discharge measurements is rather different among the gauges, not only because of their dates of installation, but also because of their conditions of accessibility during the rainy season. Figure 6 shows, for example, hydrographs of the stream gauges in 2008.

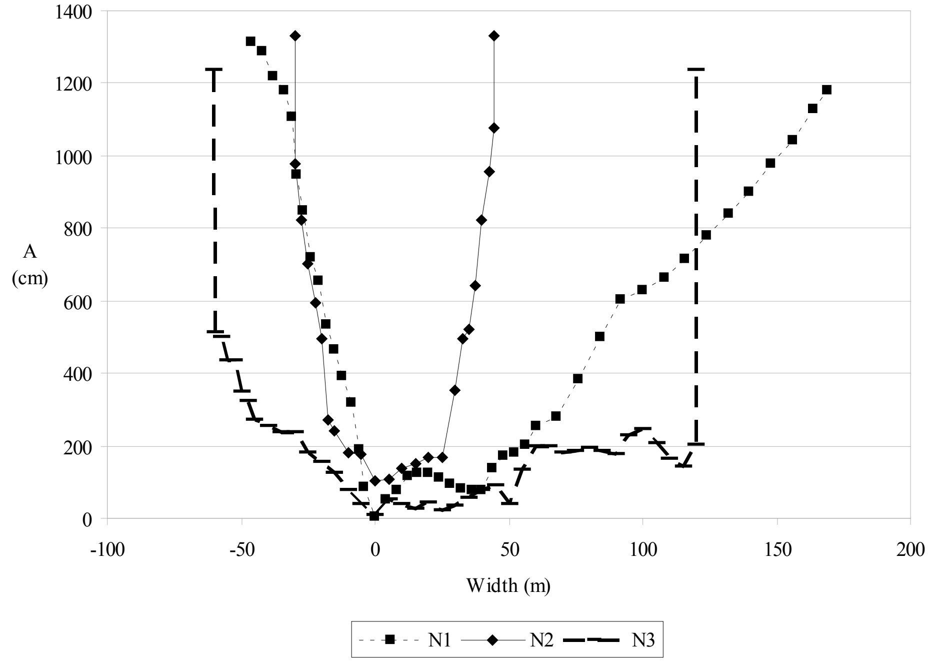

Figure 4. Cross-sections of N1, N2 and N3 stream gauges sampled in 2008 (made available by the Brazilian Geological Service), wherein A is altitude.

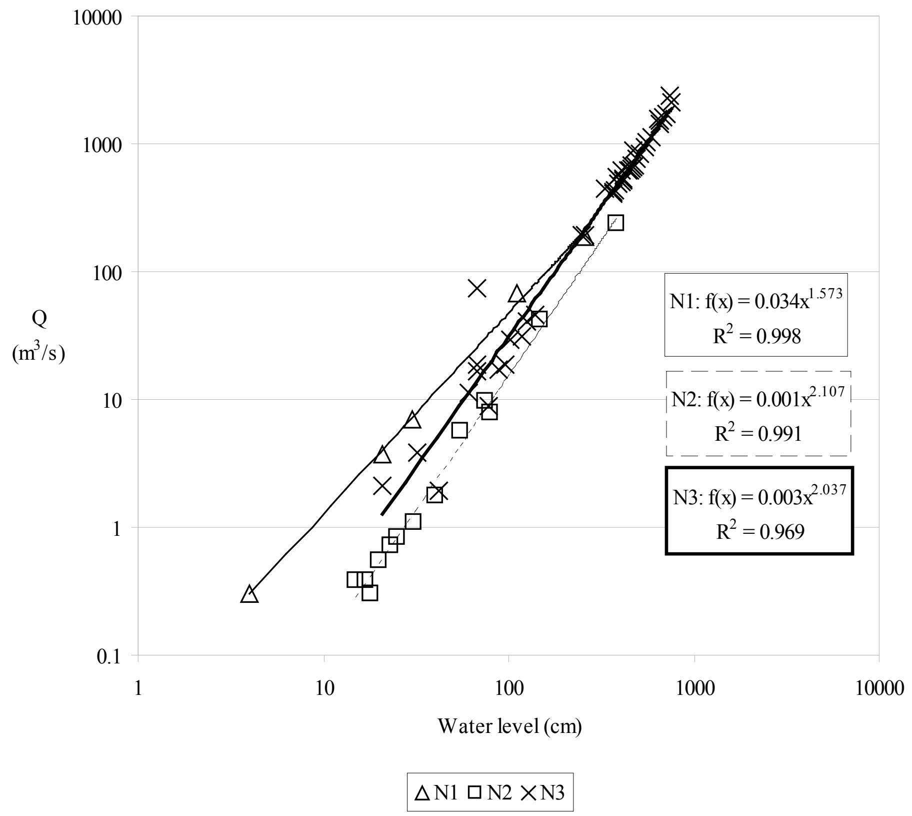

Figure 5. Rating curves of N1, N2 and N3 stream gauges, wherein water level is the difference between stream flow and streambed levels according to the rulers at the river section; and Q is discharge.

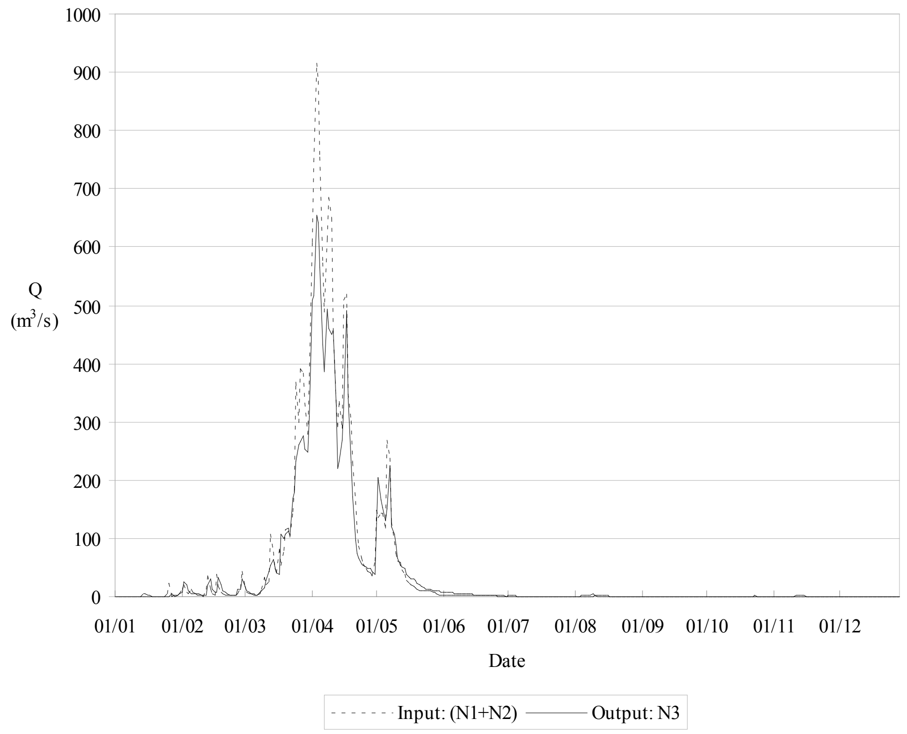

Figure 6. Hydrographs of N1, N2 and N3 stream gauges in 2008, wherein Q is discharge.

Table II shows the results of water balance analysis for 40 events monitored at JRR. The driest year was 2001, when no flow has been registered by the N3 stream gauge, and the moistest year was 2004, when the N3 and N2 stream gauges were non-functioning due to very high floods. There were also minor gaps in the stream flow series in 2002 and 2007.

Table II. Results of the water balance analysis for 40 events monitored at JRR, where N1 and N2 are the upstream gauges, N3 is the downstream gauge and the transmission losses *TL* = (O - I)/I, where O is output and I is input flow from the upstream stream gauges. The season of the event was classified in a) beginning of rainy season (BR), b) middle of rainy season (MR), c) end of rainy season (ER) and d) dry season (DS).

Date (m/y)	Event	Peak flow (N1+N2) (m^3/s)	Peak flow (N3) (m^3/s)	Input ($10^6 m^3$)			Output ($10^6 m^3$)	O - I ($10^6 m^3$)	TL (-)	Season
				N1	N2	N1+N2	N3			
4-5/2001	1	8·7	0·0	3·1	0·0	3·1	0·0	-3·1	-1·0	DS
12/2001	2	5·9	0·0	0·0	1·8	1·8	0·0	-1·8	-1·0	DS
1/2002	3	18·0	0·0	0·0	6·9	6·9	0·0	-6·9	-1·0	DS
3-6/2002†	4	48·1	30·1	24·3	21·6	45·9	32·9	-13·0	-0·3	M-ER
1/2003	5	24·8	0·0	0·0	3·6	3·6	0·0	-3·6	-1·0	DS
2-3/2003	6	77·9	83·2	23·9	21·6	45·5	59·5	13·9	0·3	BR
3-4/2003	7	444·5	272·7	211·3	83·4	294·7	232·3	-62·4	-0·2	MR
4/2003	8	23·3	34·0	3·7	7·1	10·8	17·4	6·6	0·6	MR
4-5/2003	9	22·3	30·8	4·5	1·1	5·6	10·3	4·6	0·8	M-ER
5,6-7/2003	10	97·8	67·4	21·9	8·4	30·3	30·6	0·2	0·0	ER
1-2/2005	11	15·0	0·0	2·1	0·0	2·1	0·0	-2·1	-1·0	DS
3/2005	12	6·3	0·0	0·0	3·5	3·5	0·0	-3·5	-1·0	BR
3-4/2005	13	41·2	36·0	5·3	28·3	33·6	22·8	-10·9	-0·3	MR
5/2005	14	3·9	0·0	1·0	6·1	7·1	0·0	-7·1	-1·0	ER
2/2006	15	18·7	0·0	0·0	3·8	3·8	0·0	-3·8	-1·0	BR
2/2006	16	46·8	36·0	0·0	20·3	20·3	18·6	-1·8	-0·1	BR

3/2006	17	6·3	10·1	0·0	3·8	3·8	6·1	2·3	0·6	MR
3,4-5/2006	18	328·0	63·7	28·4	370·3	398·7	175·5	-223·3	-0·6	M-ER
4,5-6/2007‡	19	175·4	50·9	52·2	40·4	92·6	55·4	-37·2	-0·4	M-ER
8-12/2007*	20	2·0	0·0	0·0	8·2	8·2	0·0	-8·2	-1·0	DS
1/2008	21	5·9	0·0	0·0	1·5	1·5	0·0	-1·5	-1·0	DS
1-2/2008	22	24·3	26·0	3·7	6·1	9·8	9·9	0·1	0·0	BR
2/2008	23	38·1	32·7	0·3	12·6	12·9	14·2	1·3	0·0	BR
2-3/2008	24	43·7	30·8	5·1	4·2	9·3	9·3	0·1	0·0	MR
3-7/2008	25	914·6	665·0	798·6	663·6	1462·2	1209·8	-252·4	-0·2	M-ER
8/2008	26	4·1	2·3	1·4	1·4	2·8	2·1	-0·8	-0·3	ER
9-12/2008*	27	1·6	0·0	0·7	7·3	8·0	0·0	-8·0	-1·0	DS
1/2009	28	2·8	0·0	0·0	0·7	0·7	0·0	-0·7	-1·0	DS
2/2009	29	0·3	2·7	0·0	0·2	0·2	0·9	0·7	4·2	BR
2/2009	30	4·1	10·1	0·0	2·1	2·1	3·3	1·1	0·5	BR
2-3/2009	31	120·0	96·7	7·2	19·3	26·5	32·7	6·2	0·2	MR
3-4/2009	32	11·5	18·3	1·3	3·4	4·7	6·6	1·8	0·4	MR
4-8/2009	33	788·3	728·3	556·8	542·0	1098·8	925·6	-173·3	-0·2	ER
8-12/2009*	34	1·7	0·7	0·3	3·9	4·2	0·0	-4·1	-1·0	DS
1/2010*	35	0·6	0·0	0·0	0·9	0·9	0·0	-0·9	-1·0	DS
3-5/2010	36	179·5	118·0	96·3	33·0	129·3	88·2	-41·0	-0·3	B-MR
5/2010	37	7·8	16·2	0·0	1·9	1·9	4·6	2·7	1·4	ER
7-8/2010*	38	2·6	0·0	0·3	0·8	1·1	0·0	-1·1	-1·0	DS
8-9/2010*	39	1·1	0·0	0·0	1·7	1·7	0·0	-1·7	-1·0	DS
9-10/2010*	40	2·1	0·0	0·0	1·8	1·8	0·0	-1·8	-1·0	DS

†Third event in the rainy season of 2002: the second one has not been registered.
‡Second event in the rainy season of 2007: the first one has not been registered.
*Event produced by release of water from upstream surface reservoirs during the dry season.

Seven events were produced by release of water from upstream surface reservoirs of JRR during the dry season. These man-made events plus ten natural ones did not reach the N3 stream gauge (TL equal to -1·0). These events had maximum input flow (N1 + N2) equal to 8·2 $10^6 m^3$ and occurred mostly during the dry season.

However, one event with 2·8 $10^6 m^3$ input flow reached the N3 stream gauge in August 2008 (26 in Table II), at the end of the rainy season. This event lost about 30% of flow through the JRR only. The rainfall spatial distribution of the rain gauges inside the JRR's drainage area (Figure 7) showed a rainfall just one day before this event, which might generate enough runoff to compensate for some of the channel transmission losses. Moreover, this event occurred after a large one, whose infiltrated stream flow may be discharged during this small event.

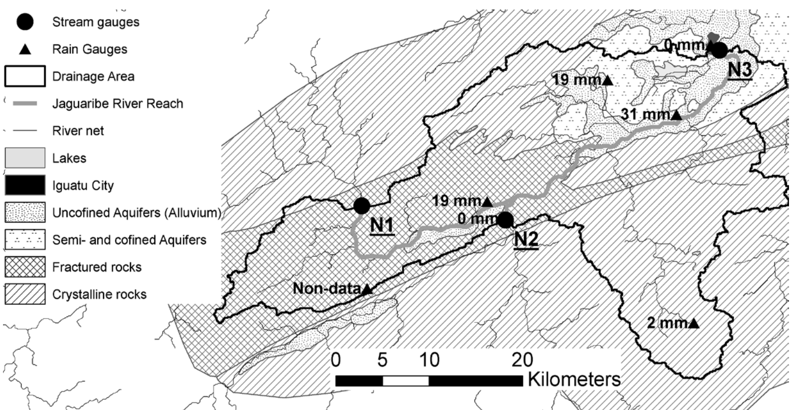

Figure 7. Rainfall spatial distribution on August 8th 2008.

Nine events between 20 and 1460 $10^6 m^3$ input flow at the middle and the end of the rainy seasons, including the largest ones, had relevant channel transmission losses ($-1·0 < TL < 0·0$) and lost at least 815 $10^6 m^3$ of river flow. All these events presented reduction in their peak flows (37% on average). However, 2 of these events (4 and 13 in Table II) presented high probability of large inflow from the drainage among the gauges, about a quarter of the inflow from the upper gauges. On the other hand, inflow from this drainage area may be negligible for the other seven events, which presented 30% of channel transmission losses on average. Therefore, a relationship between input flow and transmission losses could be estimated from these seven events (Figure 8).

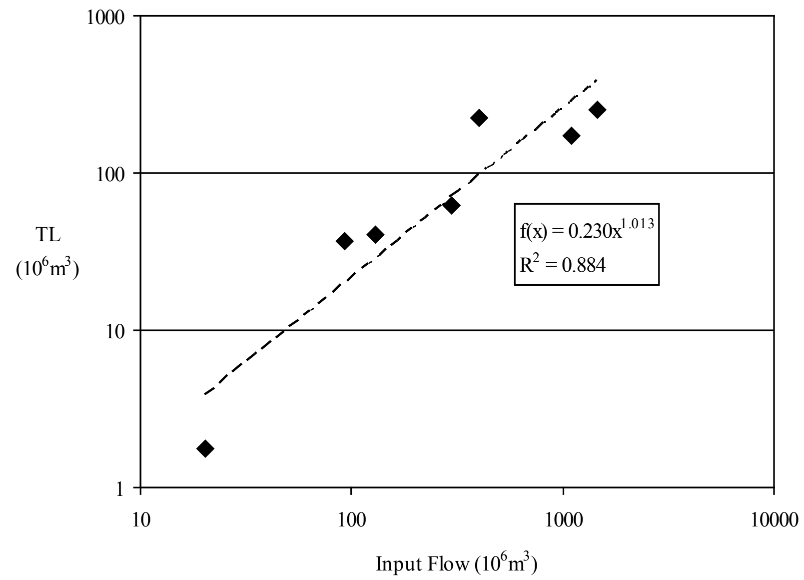

Figure 8. Input flow vs. channel transmission losses (TL) in JRR from nine events between 20 and 1460 $10^6 m^3$ input flow at the middle and the end of the rainy seasons.

On one hand, 27 of the 40 observed events lost either completely or partially (30% on average) their input river flow (N1 + N2 stream gauges). Under these events, total channel transmission losses reached at least 880 $10^6 m^3$ and peak flow was always reduced. On the other hand, channel transmission losses seemed to be compensated by or smaller than the runoff generated from the JRR's drainage area for 13 events between 09 and 60 $10^6 m^3$ input flow ($TL \approx 0·0$ or $TL > 0·0$, respectively), which could occur at the beginning, middle or end of the rainy seasons. Moreover, the events 8, 9, 10 and 37 in Table II, which occurred mainly at the end of the rainy seasons, may be influenced by the contribution of the infiltrated stream flow of the previous large events at the middle of the rainy seasons.

For the nine events with $TL > 0,0$ the upstream peak flow always increased compared to the downstream one (Table II). This is only possible if another source of inflow, e.g. the runoff of the drainage area among the gauges, besides the upstream gauges existed. For the other four events with $TL \approx 0·0$, relevant rainfall over the JRR has always been measured during the events (e.g., see Figure 9 for events in 2008 with $TL \approx 0·0$).

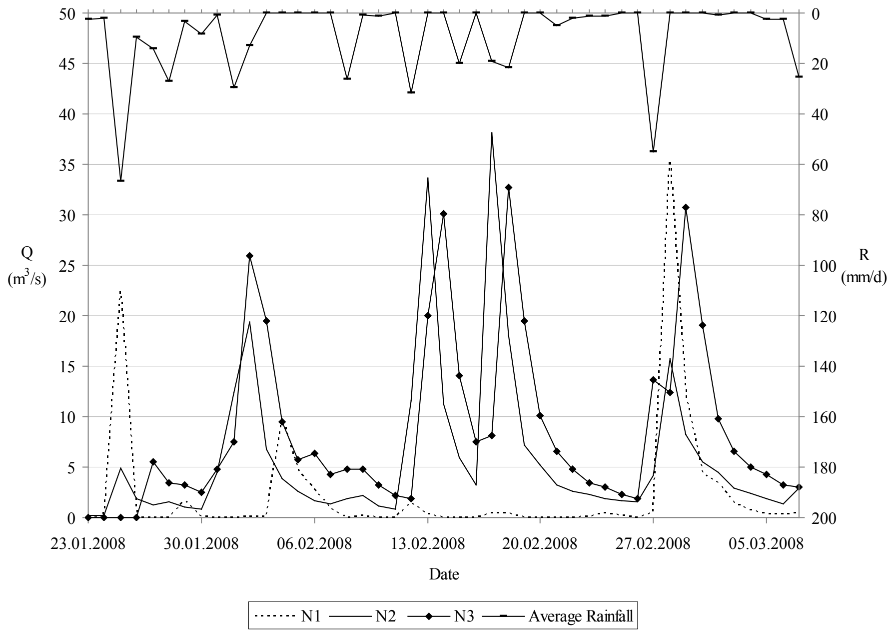

Figure 9. Stream flow (Q) and average rainfall (R) time series of events in the rainy season of 2008, whose channel transmission losses seemed to be compensated by the runoff generated from the JRR's drainage area (TL ≈ 0·0).

Groundwater level series

The groundwater level monitoring started on April 20th 2010 just as the largest event in this year took place. Only two natural events occurred in 2010: a) the largest with 1·29 $10^6 m^3$ input flow and about 30% of losses (TL equal to -0·3) from March to May 2010, and b) the second largest with 1·9 $10^6 m^3$ input and about 140% of gain (TL equal to 1·4) in May 2010, which was caused by the runoff generated from the JRR's drainage area (see previous section). Moreover, three man-made events with 100% of losses were observed during the dry season of 2010 (see Table II) from June to October.

Figure 10 shows the groundwater level and the water level of the N3 stream gauge in relation to a reference level of 25 m depth from the terrain surface of W2 well during the rainy season of 2010. The water level series ends when the non-flow situation has been registered at the N3 stream gauge.

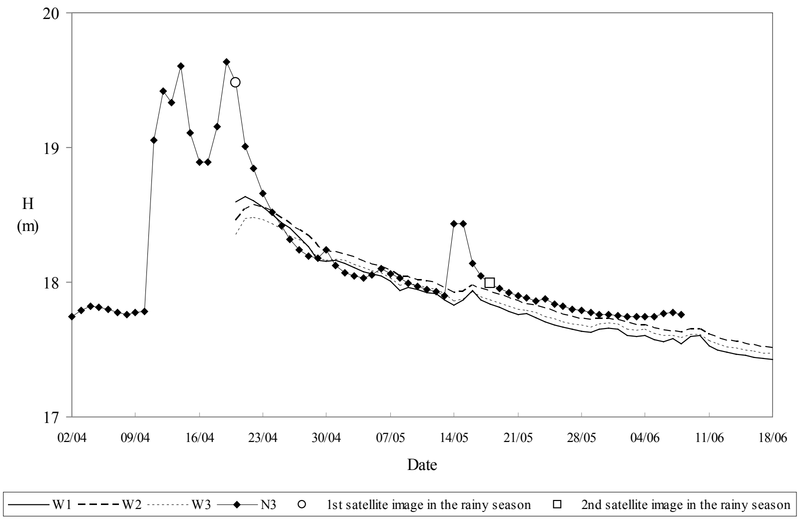

Figure 10. Groundwater level of three tubular wells (W1, W2 and W3) and water level of the N3 stream gauge (H) in relation to a reference level of 25 m depth from the terrain surface of W2 well during the rainy season of 2010 (March-May). The groundwater level monitoring started on April 20th 2010. The water level series ended when the non-flow situation had been registered at the N3 stream gauge. The days of satellite image acquisition in the rainy season are also indicated.

Figure 10 shows that

a) Water contribution from river to groundwater, i.e. channel transmission losses, was observed in two events.

b) The alluvium has shallow groundwater and the river-groundwater system can be considered to be hydraulically connected.

c) Channel transmission losses stopped during the recession limb of the larger event from April 24th to May 12th 2010, when base flow occurred, i.e. the groundwater level was slightly higher than the river's level.

d) Different from the larger event, transmission losses occurred during all smaller events, although the water balance pointed to a 140% gain in flow. The inflow from tributaries, which are closer to the N3 stream gauge and, therefore, have spatially smaller opportunity for channel transmission losses in the larger alluvial system (see Figure 2), might compensate for these channel transmission losses.

Figure 11 shows the groundwater level and the summed upstream flow of the N1 and N2 stream gauges during the dry season of 2010. The water level series of the N3 stream gauge was not shown in Figure 11 because no flow was registered at this gauge.

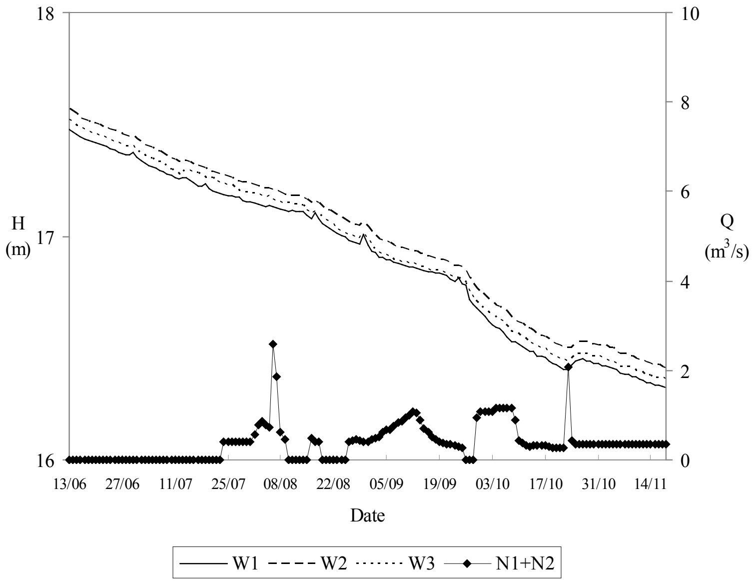

Figure 11. Groundwater level of three tubular wells (W1, W2 and W3) (H) in relation to a reference level of 25 m depth from the terrain surface of W2 well and the total upstream flows of N1 and N2 stream gauges (Q) during the dry season of 2010 (June-October). The water level series of the N 3 stream gauge was not shown here because no flow was registered at this gauge.

The man-made events (reservoir release), which resulted in 100% of channel transmission losses, had no significant influence on the evolution of the groundwater level series. Only a short peak on October 23th 2010 seemed to cause a rise in the groundwater level. Nevertheless, investigating the rainfall spatial distribution over JRR (Figure 12), we found that a heavy rainfall on October 23-24th 2010 might be the reason for the sharp peak flow on October 23th 2010 during the man-made events and the dominant inflow for the groundwater recharge in the alluvial system.

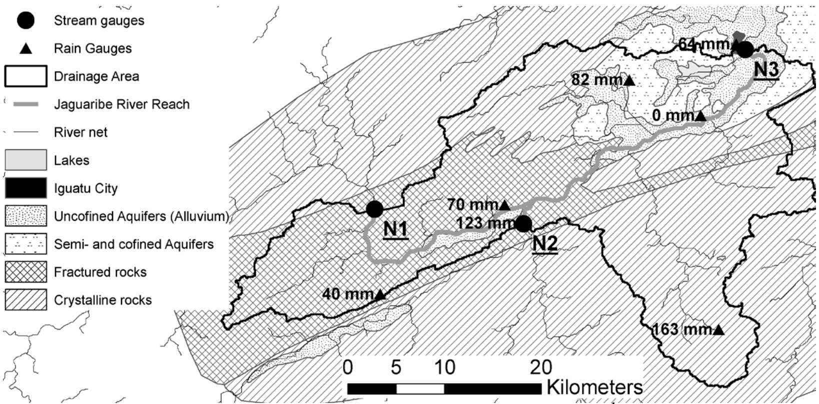

Figure 12. Rainfall spatial distribution on October 23-24th 2010.

The channel transmission losses in the large alluvial system seem to be transferred as groundwater flow to the downstream Orós reservoir, since the mean difference between groundwater level and Orós reservoir's water level was 23 m in 2010. Considering that the distance between the groundwater at N3 stream gauge and the Orós reservoir is 11 km, groundwater from this gauge had a downwards gradient to this reservoir of 2·1 m/km in 2010.

Multi-temporal satellite data

It was identified in the satellite images and proved by field work: a) that there are three overtopping weirs inside JRR (Figure 13) from which water has been taken out for agricultural and domestic use, and b) that the Jaguaribe river character changes abruptly from (i) a moderate gradient and stable cross-section stream (a riffle-dominated channel type) to (ii) a low gradient and unstable cross-section one (a meandering channel type) in the riverscape region displayed in Figure 14.

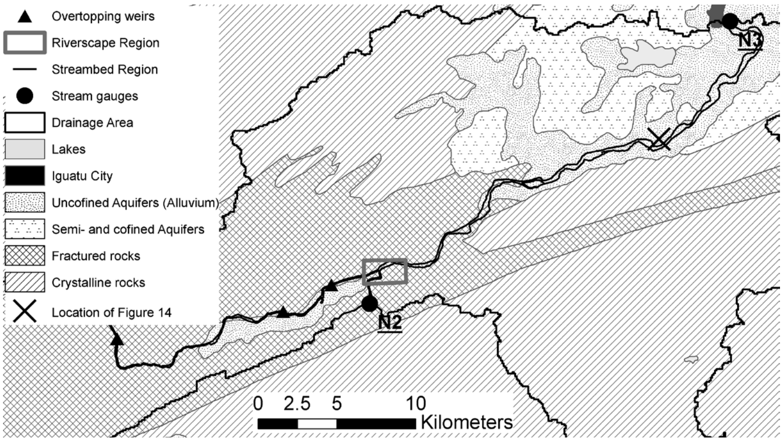

Figure 13. Location of the three overtopping weirs inside JRR.

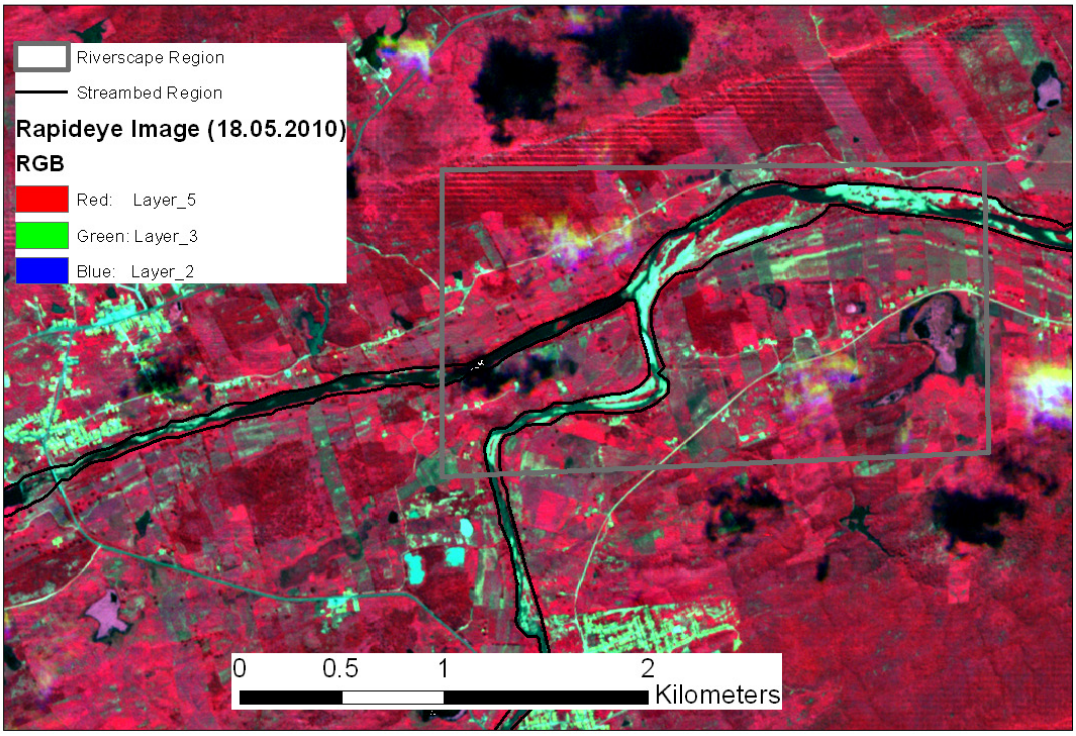

Figure 14. The riverscape region, where the characterist of the Jaguaribe river changes abruptly from (i) a moderate gradient and stable cross-section stream to (ii) a low gradient and unstable cross-section one. False colour composite image (Red= NIR, Green= red and Blue= green) collected on May 18th 2010.

The existence of overtopping weirs and, additionally, the change in river character suggested that channel transmission losses might not be relevant upstream of these weirs. Instead, the losses may occur mainly downstream of them, in the large alluvial system characterized by unconfined aquifers (see Figure 13).

Moreover, we observed connected surface water throughout the whole JRR in the satellite image mosaic collected in 2009 during the dry season, when no flow was registered at the stream gauges. Upstream of the overtopping weirs, the surface water was clearly a result of water retention by them. Downstream of them, the surface water might percolate into the shallow groundwater in the alluvium system.

Water coverage inside JRR from the images collected on April 20tth 2010 (exactly one day after the peak flow during the rainy season) and on May 18th 2010 (during the flow recession limb) was concentrated inside the streambed region of JRR (Figure 15).

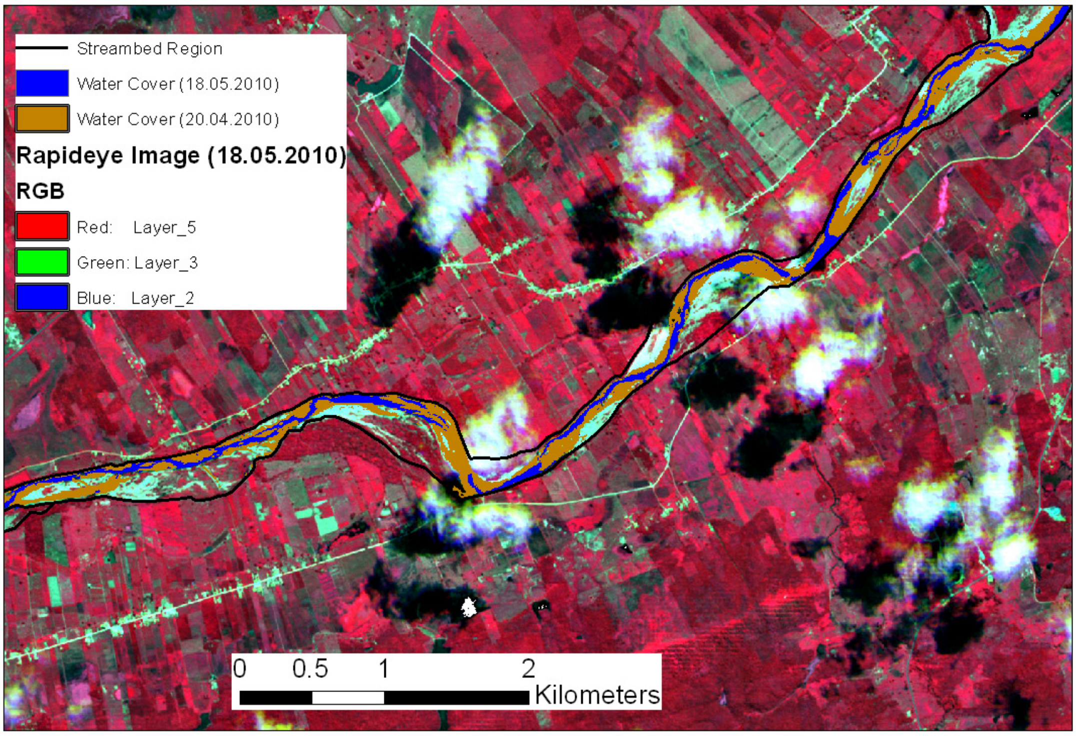

Figure 15. Details of water cover inside JRR from images collected on April 20th 2010 (exactly one day after the peak stream flow during the rainy season) and on May 18th 2010 (during the stream flow recession limb). False colour composite image (Red= NIR, Green= red and Blue= green) collected on May 18th 2010. The location of this Figure in JRR was displayed in Figure 13a.

In this respect, river flows with a maximum of 118 m^3/s at the N3 stream gauge - the peak flow during the rainy season of 2010 - are certainly confined within the streambed and banks without inundating the floodplains. Hence, channel transmission losses of 24 from the 27 events analysed previously, which lost their input river flow either completely or partially, infiltrated through streambed and banks only.

Furthermore, a discharge decrease at the N3 stream gauge from 995 m^3/s on April 20th 2010 to 2·4 m^3/s on May 18th

2010 (97·6 %) was equivalent to an area reduction of water coverage from 340 ha to 127 ha in the JRR between the overtopping weir furthest downstream and the N3 stream gauge (62·8 %) (see Figure 13).

DISCUSSION AND CONCLUSION

Hydrological concept

Channel transmission losses in a 60-km long reach of the Jaguaribe river (JRR) have been analysed by stream flow series, groundwater level series and multi-temporal satellite data. Such losses occur through natural causes during the dry and rainy seasons and by man-made events during the dry season, which are produced by release of water from upstream surface reservoirs into JRR. They take place mainly in a large alluvial system with shallow groundwater and extending about 30 km along the JRR. The river-groundwater system in this alluvium can be considered to be hydraulically connected.

The "flow paths" of transmission losses have been analysed too. Most transmission losses certainly infiltrated only through streambed and banks and not through the flood plains, as could be shown by satellite image analysis. Moreover, after upstream discharge events, transmission losses can return to the channel as base flow when the groundwater level is higher than that in the river, as also observed by Lima *et al.* (2007).

Seventeen natural and man-made floods during the dry seasons, whose input flows from the upper stream gauges were smaller than a runoff threshold of 8·2 $10^6 m^3$, did not reach the outlet of JRR. A runoff threshold was also identified by Knighton and Nanson (1994) in the Cooper Creel River in Australia.

A clogging layer in the streambed, which is capable of allowing river flow transmission of small floods as hypothesised by Lange (2005), might not occur in JRR because of that runoff threshold. Moreover, man-made events (reservoir releases) during the dry season in 2010 had no significant influence on the evolution of the groundwater time series, which might be explained by the extraction of groundwater for agricultural use and/or by flow damping in the alluvium during the groundwater wave propagation.

Seven floods between 20 and 1460 $10^6 m^3$ at the middle and the end of the rainy seasons reached the outlet, losing on average 30% of their input river flow. Input flows which achieve the outlet in the 420 km channel reach of the Cooper Creel River, Australia, lost about 75-80% on average (Knighton and Nanson, 1994) and 60% in the 150 km channel reach of the Kuiseb River, Namibia Desert, (estimated from Table II in Lange, 2005). The Jaguaribe river flows also suffered a reduction of 37% in their input peak flow, which could also be an effect of flow damping in the river.

Furthermore, we found that the higher the input river flow, the higher the channel transmission losses (see Figure 8), underlining the considerable role played by high floods on channel transmission losses. This result is also supported by Knighton and Nanson (1994), Lange *et al.* (1998) and Lange (2005); however, no runoff threshold was identified at high discharges.

Most probably the influence of the floodplains and the effects of clogging layers on the channel transmission losses at high discharges can be rejected. However, we still cannot determine whether the hydraulic head at the surface and/or the microlayering alluvial sediments at the streambed control the transmission losses during the high floods.

In general, we observed 27 transmission losses events in JRR during 10 years, which amounts to at least 880 $10^6 m^3$ of river flow losses. However, since the groundwater from the outlet of JRR had a slope towards the downstream Orós reservoir of 2·1 m/km in 2010, which is located over the same large alluvium-system that JRR crosses, we hypothesise that the losses to shallow groundwater return to the surface in this downstream reservoir. If this hypothesis is true, the groundwater component of Orós reservoir's water balance needs to be considered when estimating its medium-term water release for agricultural and domestic use.

Modelling and simulation strategies

Channel transmission losses in JRR can be conceptually described as follow:

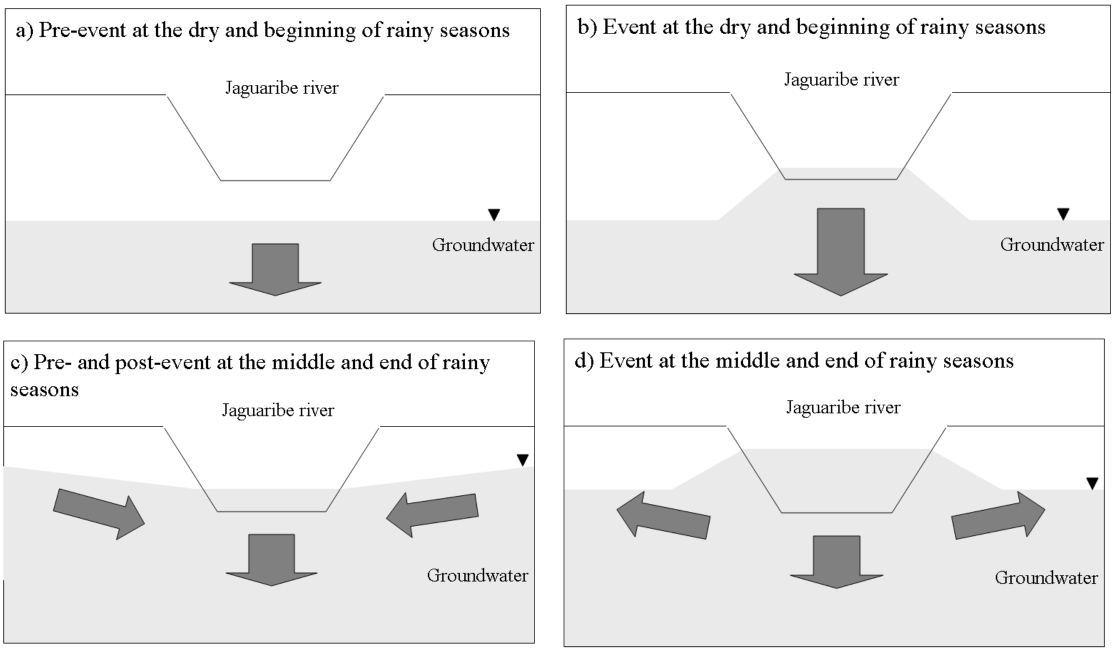

Figure 16. Conceptual description of channel transmission losses in the Jaguaribe river reach.

On the one hand, during the dry and at the beginning of rainy seasons, no river flow is expected for pre-events (Figure 16a) and events have predominantly vertical infiltration into the alluvium (Figure 16b). On the other hand, at the middle and end of the rainy seasons, river flow sustained by base flow occurs before and after events (Figure 16c) and lateral infiltration into the alluvium plays a major role during events (Figure 16d). Thus, the hydraulically connected Jaguaribe river reach shifts from being a losing river at the dry and beginning of rainy seasons to become a losing/gaining (mostly losing) river at the middle and end of rainy seasons.

Due to this seasonal behaviour, channel transmission losses model based on a Green-Ampt infiltration approach as carried out by Abdulrazzak and Morel-Seytoux (1983) and Illangasekare and Morel-Seytoux (1984) should not be implemented, because it accounts only for hydraulically connected losing rivers. Instead, the leakage concept for river-aquifer interaction (Rushton and Tomlinson, 1979), which allows modelling of connected losing/gaining rivers, is more suitable (see e.g. Xie and Yuan, 2010).

In this way, a conceptual hydrological model based on the channel transmission losses in JRR explained above can be a coupling of river groundwater flow models linked by a leakage concept-based approach, which takes into account a variable hydraulic head at the surface. This modelling strategy has been mostly undertaken in humid and temperate catchments (see e.g. Engeler *et al.*, 2011; Krause and Bronstert, 2007) and not in arid and semi-arid ones.

However, the actual data scarcity of the underlying alluvium and the groundwater extraction during the dry seasons might constrain the application of distributed groundwater flow models to JRR's channel transmission losses. Therefore, if more data are not to be sampled for groundwater flow modelling, a simplified approach should be adopted. For example, Niu *et al.* (2007) assumed the underlying unconfined aquifer as a reservoir, wherein the temporal variation of the water stored in this reservoir is equal to the water balance between recharge and discharge flows.

Also based on this discussion, Costa et al. (2011) developed a new semi-distributed channel transmission losses model for different dryland rivers. They applied it to the studied Jaguaribe river reach using the conceptual model presented in this research and simulated reliably stream flow volume and peak of selected rainy seasons.

They also tested different model structures beyond this conceptual model, in order to reduce model structure uncertainties and to guide future field campaigns for the investigation of the dominant processes in the JRR. They found that both lateral stream-aquifer water fluxes and groundwater flow in the underlying alluvium parallel to the river course are necessary to predict stream flow and channel transmission losses, the former process being more relevant than the latter.

As an empirical approach, the relation shown in Figure 8 may be applied to input river flow between 20 and 1460 $10^6 m^3$ to estimate event-based channel transmission losses

$$V_{TL} = 0.230\, V_{IF}^{1.01} \qquad (2)$$

where V_{TL} is transmission losses ($10^6 m^3$) and V_{IF} is input river flow ($10^6 m^3$). From a realistic point of view, only the order of magnitude of the simulation using Eq. (2) should be taken in account, since the relationship was based on a rather limited number of measurements (see Figure 8). Nevertheless, dividing the terms of Eq. (2) by the river reach extension contiguous with the alluvium, about 30 km, one can estimate roughly channel transmission losses per km for similar ungauged hydrogeologic areas.

Further work

We intend to extend the groundwater level monitoring within the Jaguaribe river reach and also to sample groundwater extraction data in the alluvium through interviews with locals and farmers.

A critical point is the derivation of parameters from the alluvium for groundwater modelling in JRR. We will need a) the distribution of saturated hydraulic conductivities in the alluvium and in its boundary, and b) the geometry of the alluvium. Based on the depth and the texture information of borehole stratigraphies, we can apply an indicator geostatistical approach to derive a) and b) for JRR, as done by Carle and Fogg (1996; 1997) and Carle *et al.* (1998) for alluvial fans and fluvial deposits in California, USA. However, several borehole stratigraphies should be undertaken in the area.

In this paper, we have shown how satellite images can help with the understanding of channel transmission losses in large dryland rivers. The river reach studied has been monitored by stream gauges, however, most of dryland river reaches are ungauged. How to infer channel transmission losses in large ungauged dryland rivers? We propose to combine the analysis of the satellite images, e.g. as undertaken in this work, with high resolution digital elevation models (DEMs) of riverscapes.

A high resolution DEM and water surface extent maps from satellite images can provide volume extent maps of river reaches. Since the DEM and the satellite images give information about riverbed and floodplain slopes and riverscape cover, respectively, the order of magnitude of the river reach average velocities can be also estimated by e.g. Manning's equation. Comparing the volumes and average velocities of two cascade river reaches during a flood, we can then infer channel transmission losses if and only if the volume and the velocity of the downstream reach are smaller than the volume and the velocity of the upstream reach, which means that the discharge through the upstream reach is higher than the discharge through the downstream reach. Furthermore, we think that this remote sensing-based method can be applied not only to dryland rivers, but to wetland rivers as well. We plan to test this approach for large rivers, where water levels at river sections and groundwater level data are more easily available.

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