Downstreamness: A Concept to Analyze Basin Closure

P. R. van Oel[1]; M. S. Krol[2]; and A. Y. Hoekstra[3]

Abstract: In many places in the world, increasing water demands have led to the development of infrastructure for freshwater storage and irrigation. Especially in water-scarce regions, this development has led to a growing number of concerns about basin closure. These concerns ask for a structured approach for analyzing the occurrence of basin closure to facilitate sustainable responses. In this paper, the *downstreamness* concept is proposed for analyzing the availability and commitments of freshwater in river basins. The downstreamness of a location is the ratio of its upstream catchment area to the entire river basin area. The downstreamness of a function on the basin, such as water availability or water demand, is defined as the downstreamness-weighted integral of that function divided by its regular integral. An approach to determine the downstreamness of surface water storage capacity, stored surface water volumes, and water demands is described. Applying the proposed approach is helpful for the spatiotemporally explicit assessment of basin closure and its drivers. Water management policies rely on the valuations of trade-offs between commitments of upstream and downstream uses and technical implementations of upstream and downstream measures. The concept of downstreamness can assist in analyzing subbasin points of view as an integral part of a basin perspective. In this way, the effects of anthropogenic processes driving basin closure can be better understood. To illustrate the use of the concept, the authors describe its application to the Jaguaribe Basin in the semiarid northeast of Brazil. **DOI: 10.1061/(ASCE)WR.1943-5452.0000127.** *© 2011 American Society of Civil Engineers.*

CE Database subject headings: River basins; Water shortage; Brazil; Arid lands.

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Introduction

An increasing amount of research is devoted to basin closure (Seckler 1996; Svendsen et al. 2001; Molle 2004; Molden 2007; Falkenmark and Molden 2008; Molle 2008; Smakhtin 2008; Wester et al. 2008; Molle et al. 2010). According to Seckler (1996), a basin is closed if no usable water leaves it, that is, when all available runoff has been consumed or polluted. In concept, environmental flow requirements are highly valued and are not considered to be part of available runoff. Accordingly, Molle et al. (2007, 2010) consider river basins or subbasins to be closing when commitments with regard to societal and environmental freshwater needs cannot be met for part of the year, and to be closed when commitments cannot be met during the entire year. In the terminology of the water footprint (Hoekstra et al. 2009), basin closure occurs when blue water availability within a basin equals the blue water footprint in that basin (Hoekstra et al. 2009), where blue water availability is the natural runoff from the catchment minus the environmental flow requirement. Examples of overcommitted basins are the Colorado, the Indus, and the Murray-Darling basins (Molle et al. 2010). The inability to meet commitments may vary in space and time and may be influenced by a combination of natural factors (e.g., topography and rainfall intensity) and human activities (e.g., surface water storage and water use). Infrastructural development may lead to the overdevelopment or overbuilding of basins (Molle 2008). Water use in upstream locations subtracts from water availability in downstream locations. Human-induced storage in upstream locations (dams) can both increase and decrease water availability at downstream locations, depending on actual water management (reservoir operation). Storage in reservoirs generally aims to increase runoff in times of natural shortages, during which the increased runoff may be managed to supply water to water users located directly around or downstream of a reservoir. However, it also leads to decreases in total runoff because of increased evaporation from reservoirs. In the present literature about basin closure, no concepts or methods are described for the systematic analysis of basin closure as a phenomenon that can appear at various locations and moments in a river basin. As a result, the influence of natural and human factors on a basin's runoff often remains unclear, and the contributions of different subbasins to the closure of an entire river basin are generally not addressed separately.

To characterize locations within the topography of a basin, the concept of downstreamness was introduced by van Oel (2009), by considering the area of the subbasin upstream from that location. The downstreamness of a location (or spatial entity) is the ratio of this upstream catchment area to the entire river basin area. The downstreamness ranges from 0, for mountain peaks in the basin, to 1 at the mouth of the basin. The downstreamness of a function on the basin (e.g., water availability or water demand) is defined as the downstreamness-weighted integral of that function divided by its regular integral. The concept was developed to explain how physical conditions for the good manageability of water resources through surface water storage improve or worsen from up- to downstream at a river basin level (van Oel et al. 2009).

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The concept of downstreamness can be beneficial for the analysis of the distribution of water resources and water use over space and time, also referred to as 'waterscape' by Venot et al. (2007). In this paper, the downstreamness concept is used to more systematically assess (1) the spatiotemporal variability of the processes driving basin closure; and (2) the influence of natural and human factors on a basin's runoff. Doing this allows for analyzing the contribution of individual projects, such as dams and irrigation schemes, to the process of the closure of a basin or subbasin. To illustrate the use of the concept, it is applied to the Jaguaribe Basin in the semiarid northeast of Brazil.

Method

Basin Closure

To get a first impression of closure at selected locations in a basin, it is proposed to compare runoff (e.g., seasonal or annual) to changes in stored volumes over the same period of time for various locations and periods of time (Storage change–actual runoff diagram, Fig. 1). In areas with a distinct wet period (e.g., semiarid areas), runoff in the wet period serves partly to increase water storage in artificial reservoirs and partly to supply the river with basic flow requirements. Increases in stored volumes, ΔS, and actual runoff, Q, over a period approximately add up to natural runoff, Q_{nat}, during that period, if evaporative losses over the wet period are neglected. The natural runoff determines the position of a diagonal in Fig. 1 for which ΔS and Q add up to Q_{nat}. This diagonal will be positioned closer to zero in case of relatively dry periods, because the natural runoff is low in this case. The ratio between ΔS and Q determines the relative position of a data point on the diagonal closer to the x-axis or to the y-axis. Obviously, the storage capacity and the stored volumes at the beginning of the analyzed period are very important.

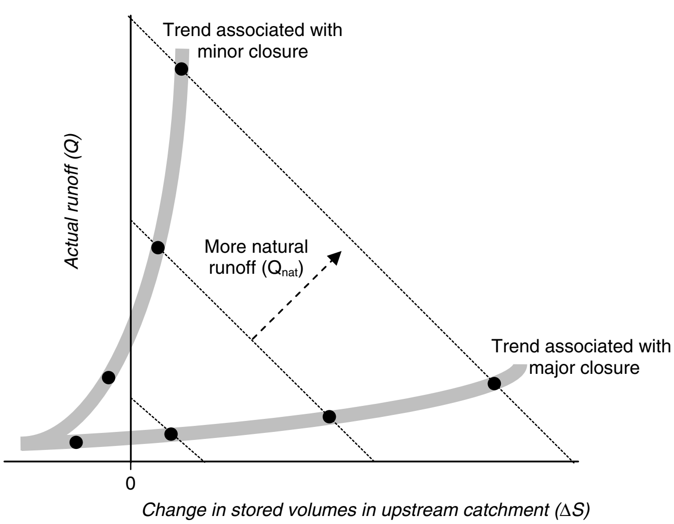

Fig. 1. Storage change–actual runoff diagram; the relationship between changes in stored volumes, ΔS, upstream of a specified location in a basin and downstream runoff, Q, over a period of time, in a common volumetric unit, can be used as an indicator of closure at that location; a point that represents the ratio between actual runoff and stored volume changes associated with the amount of natural runoff, Q_{nat}, over a period of time may be identified on the diagonal; a point close to the ΔS axis indicates closure

In a case in which storage capacity is negligible in relative terms, little natural runoff will be retained. In this case, basin closure through artificial storage is minor and is represented by a rather vertical orientation of data points for different measurements at different moments at a selected location. Reversely, if a large share of natural runoff is retained in storage facilities, basin closure may be significant. In this case, data points may be oriented more horizontally in Fig. 1. Because of the nature of flow in a basin, runoff is always positive. Changes in storage can, however, be both positive and negative.

Downstreamness

Topography determines the direction of natural freshwater flow in a basin. Actual runoff is mostly influenced by rainfall, evapotranspiration, ground water storage, surface water storage, and water use. The direction of flow accumulation can be determined by using a digital elevation model of a basin. Every location x in a river basin can be characterized by the size of its upstream catchment area. To include the spatial extent of a river basin, the upstream area, $A_{\text{up},x}$, is divided by the total catchment area of the river basin, A_{tot}, the fraction determined is called downstreamness, D_x:

$$D_x = \frac{A_{\text{up},x}}{A_{\text{tot}}} \times 100\% \qquad (1)$$

The downstreamness of a function on the basin is defined as the downstreamness-weighted integral of that function divided by the regular integral of that function. For a function defined on a discrete set of locations in the basin, the downstreamness is similarly defined as the downstreamness-weighted sum of the function divided by the regular sum [e.g., Eqs. (2)–(4)]. When flow measurements are available for multiple locations in a basin, a spatial depiction of basin closure and subbasin closure can be made (Fig. 2). By definition, increasing downstreamness implies a larger upstream catchment area; natural runoff is expected to increase with increasing downstreamness. Irregularities may occur in cases for which spatial variations in rainfall and land cover in parallel subbasins exist in which streams are not physically connected until they meet further downstream (i.e., locations along streams of separate subbasins may have the same downstreamness but may be influenced by different circumstances, resulting in a scatter plot rather than one continuous line). Runoff at downstream locations lower than at upstream locations might be attributable to natural influences such as evapotranspiration, natural storage and infiltration in the river bed, or human influences on the hydrological cycle such as storage behind artificial dams and water abstractions for irrigation.

In the subsequent subsections, the downstreamness of storage capacity, stored volume and water demand are defined. All three indicators may be useful for analyzing basin closure. By comparing the downstreamness of storage capacity to the downstreamness of actual stored volumes, one can evaluate whether a (sub-) basin is closed or not. By analyzing the downstreamness of water demand, one can compare the vulnerability of different types of demand. Such an analysis may also give insights into the causes of closure because demand is a good indicator of water use.

Downstreamness of Storage Capacity in Reservoirs

For analyzing the downstreamness of a basin's storage capacity, the capacity of reservoirs and the locations of dams are relevant. The downstreamness of the total storage capacity in a basin, D_{SC}, can change over time attributable to newly built reservoirs or capacity loss by sedimentation. For a basin with n reservoirs, D_{SC} is

$$D_{\text{SC}} = \frac{\sum_{x=1}^{n} \text{SC}_x D_x}{\sum_{x=1}^{n} \text{SC}_x} \qquad (2)$$

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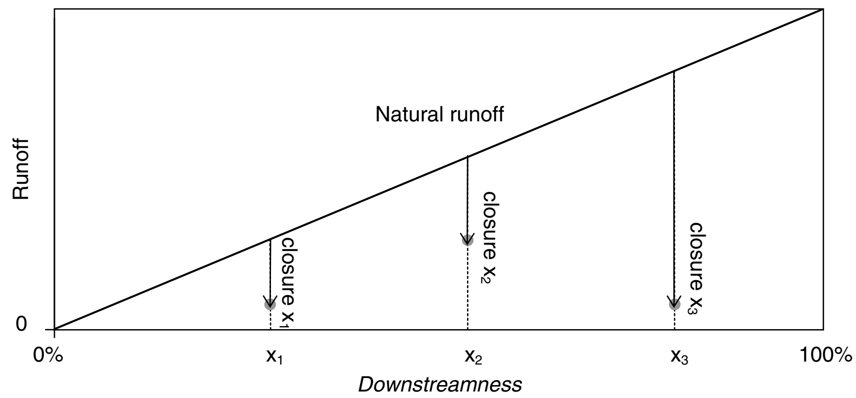

Fig. 2. Closure in a hypothetical basin at measurement locations x_1, x_2, and x_3; these locations are all outlets of subbasins, as are, in fact, all locations inside a basin; the diagonal represents natural runoff that increases linearly with downstreamness; this implies homogeneous conditions; no losses in the river network are assumed; the distance between a plotted point and the diagonal with the same x-coordinate is an indication of the closure caused in the catchment of the measurement location; closure may be caused by storage in reservoirs or by water abstractions for consumptive use

where D_x = downstreamness of reservoir x; and SC_x = storage capacity of reservoir x. D_{SC} is a measure of how far downstream storage capacity in the basin is located on average.

Downstreamness of Stored Volumes in Reservoirs

For analyzing the downstreamness of stored volumes in reservoirs, D_{SV}, in a basin, reservoir volumes and the locations of the dams are relevant. D_{SV} changes because volumes at different locations can change over time at different rates. For a basin with n reservoirs, the D_{SV} is

$$D_{SV} = \frac{\sum_{x=1}^{n} SV_x D_x}{\sum_{x=1}^{n} SV_x} \quad (3)$$

where D_x = downstreamness of reservoir x; and SV_x = stored volume in reservoir x. D_{SV} is a measure of how far downstream stored water in the basin is located on average.

Downstreamness of Water Demand

For analyzing the downstreamness of water demand, D_{WD}, the actual locations of water users and their demand are relevant. For the agricultural sector, water demands related to (irrigated) crops cultivated in a basin area in geographical units with a specified location are relevant. For a basin with n geographical units, D_{WD} is

$$D_{WD} = \frac{\sum_{x=1}^{n} WD_x D_x}{\sum_{x=1}^{n} WD_x} \quad (4)$$

where D_x = downstreamness of water demand at location x; and WD_x = water demand of location x. D_{WD} is a measure of how far downstream water demand in the basin is located on average.

Study Area

The Jaguaribe Basin is located in the state of Ceará and covers approximately $74,000\ km^2$ (Fig. 3). Annual precipitation ranges

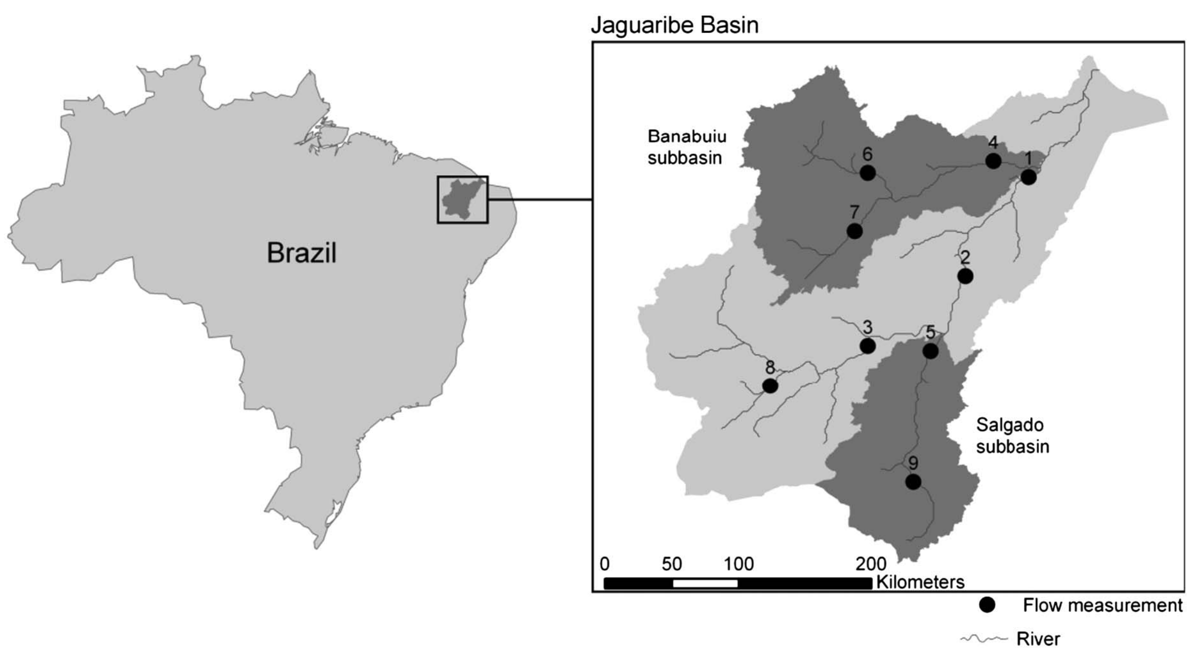

Fig. 3. The Jaguaribe Basin in the semiarid northeast of Brazil; numbers represent the measurement stations used in this paper; for each station, the downstreamness and total upstream storage capacity are given in Table 1

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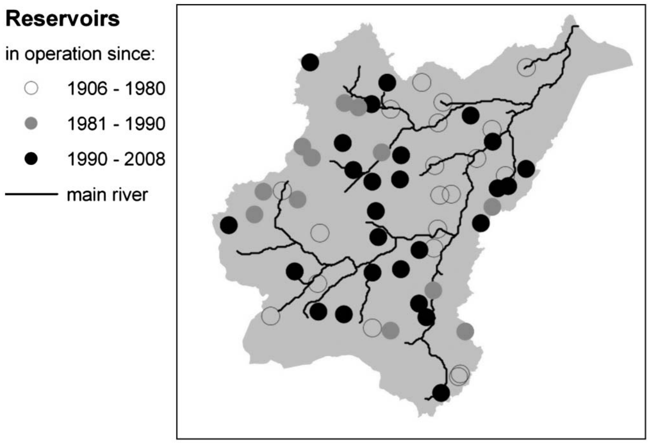

Fig. 4. Locations of dams analyzed in this study

from 450 to 1,150 mm, on average, with high levels of temporal and spatial variability [Fundação Cearense de Meteorologia e Recursos Hídricos (FUNCEME) 2008]. Rainfall is concentrated from January to June. Temporal rainfall variability is highly significant on a range of levels: decadal variability (Souza Filho and Porto 2003), interannual variability, seasonal variability, and variability on the time scale of a week (Uvo et al. 1998; Smith and Sardeshmukh 2000; Gaiser et al. 2003). Runoff coefficients for subbasins amount to approximately 10–20% (Guntner et al. 2004). The area has a history of recurrent water stress (Guerra and Guerra 1980; Villa 2000; Gaiser et al. 2003), which is related to both rainfall variability and human intervention. Historically, the river used to be dry at the outlet for several months a year. To deal with this situation, many dams have been constructed (Fig. 4). The present situation has lead to increasing concerns of basin closure (van Oel 2009). Water use is dominated by abstraction for irrigation. Water allocation among alternative (agricultural) uses in the Jaguaribe Basin are intensely discussed because of the persistent pressure on water reserves in strategic reservoirs [Companha de Gestão dos Recursos Hídricos (COGERH) 2001; Döll and Krol 2002; Lemos 2003; Krol and van Oel 2004; Lemos and De Oliveira 2004; Johnsson and Kemper 2005; van Oel et al. 2008, 2009, 2010). Commercial production of fruit and flowers is increasingly common in the basin [Secretaria de Agricultura e Pecuaria do estado Ceará (SEAGRI) 2003, 2005]. In Fig. 5, the downstreamness of geographical units is indicated and categorized on the basis of grid cells and municipal districts. For determining the downstreamness, use was made of a 90 × 90 m resolution digital elevation model of the river basin (EMBRAPA 2006).

For the Jaguaribe Basin, nine measurement locations (Fig. 3) were selected for which both data about runoff and about upstream storage volumes in public reservoirs at the end of the wet season are available. In Table 1, the measurement stations and the upstream storage capacity are given.

Data from an online database of the Brazilian national water agency [Agência Nacional de Águas (ANA) 2009] were used for annual runoff. For reservoir capacity and stored volumes for the primary reservoirs in the Jaguaribe Basin, use was made of data from an annual monitoring report by the Ceará state authority for water management (COGERH 2007). Reservoir volumes are given for the end of the wet season (July 1). Data from the online agricultural production database of the Brazilian institute for geography and statistics [Instituto Brasileiro de Geografia e Estatistica (IBGE) 2009] has been used to indicate agricultural water demands.

Results

Downstreamness and Runoff: Measuring Closure at Multiple Locations in the Jaguaribe Basin

A comparison of runoff and upstream stored volumes for two measurement stations is presented in Fig. 6. For one of the stations (4 Morada Nova), the upstream storage capacity is large in relation to downstreamness (Table 1), with capacity exceeding the average annual upstream generated runoff. Runoff is strongly influenced by processes associated with basin closure, as is reflected in the horizontal orientation of points in the figure. For the other station (5 Icó), upstream storage capacity is modest in relation to downstreamness (Table 1), with a capacity of approximately a third of the average annual upstream natural runoff. Runoff is much less affected, indicating a low level of closure in the subbasin, consistent with the vertical orientation of the data points in Fig. 6.

At these two stations, runoff never dropped down to zero for the entire year. In this sense, the (sub-) basin is not to be regarded as closed. Environmental flow requirements or other commitments that may not have been met are ignored in this paper, however.

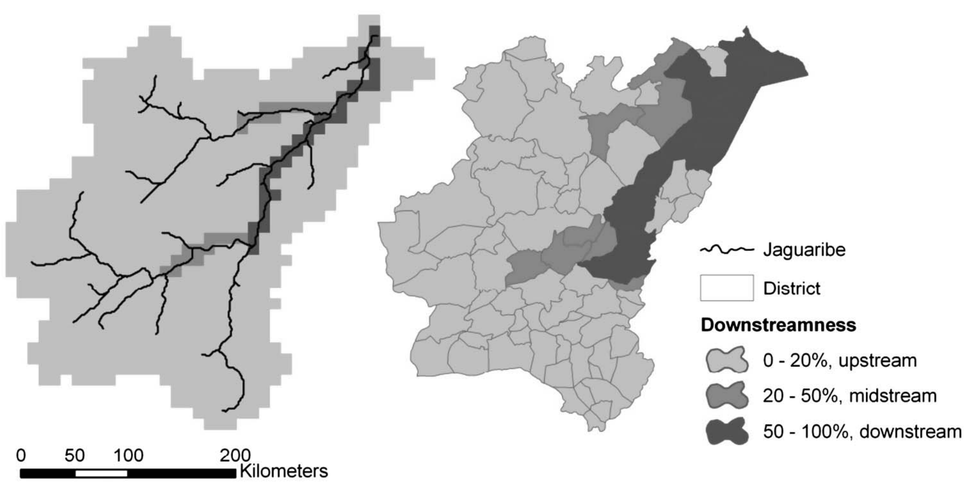

Fig. 5. Downstreamness of geographical units in the Jaguaribe Basin; the downstreamness of a district as a whole is measured at its most downstream point

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Table 1. Runoff Measurement Stations, Upstream Storage Capacity in Public Reservoirs, and Downstreamness

Measurement station	Upstream storage capacity (10^9 m^3)	Downstreamness
1 Peixe Gordo	9.87	65%
2 Jaguaribe	3.02	54%
3 Iguatu	0.32	28%
4 Morada Nova	2.70	24%
5 Icó	0.40	16%
6 Quixeramobim	0.29	10%
7 Senador Pompeu	0.19	7%
8 Malhada	0.07	5%
9 Podimirim	0.14	4%

From the trends in Fig. 6 the process of closure can be clearly observed. The data points in Fig. 6 represent annual values for actual runoff and changes in storage in the catchment upstream of the measurement stations. If upstream storage values show an increase while downstream runoff is low, it is a clear indication that closure is taking place. For cases for which closure in the subbasin is taking place, data points are expected to be horizontally orientated and close to the *x*-axis (low runoff), indicating that available water is consumed upstream, and demand adapts to availability. For Measurement Station 4 (Morada Nova), there has been an increase in stored volumes in combination with relatively low runoff for several years (data points). The actual runoff seriously increases only in cases of extreme natural runoff because storage capacity is saturated.

For Icó, the opposite process is observed. In this case, higher upstream natural runoff leads to higher runoff at the station and only limited increases in storage. No closure is indicated by the data that are all close to the *y*-axis in the figure.

When analyzing closure for the entire basin, a typical trend is observed at different spatial levels using the downstreamness concept. From upstream to downstream (with increasing downstreamness), runoff first increases and then decreases again. For average annual runoff, this trend is observed at the basin level (Fig. 7). Also in this figure, the difference between Measurement Stations 4 and 5 is shown. For interpreting the results that are presented in Fig. 7, it is important to realize that measurement stations are not all directly connected through the river network. The runoff at both Stations 3 and 5 (in parallel subbasins) routes to Stations 2 and 1. This indicates that the sum of runoff at Stations 3 and 5 can be compared to runoff at Stations 2 and 1 (see Fig. 3 for the exact positioning of measurement stations). However, Station 4 is positioned on a river branch that merges with the primary Jaguaribe River only downstream of Station 1 (see Fig. 3). Ideally, a measurement station at the outlet of the entire river basin should also have been included because for actual runoff at the outlet of a river basin, the situation in the entire basin (including all measurement stations) is relevant.

For runoff in a dry year (Fig. 8), closure is observed at various locations in the basin. In Fig. 8, in some years (i.e., 2001, in this case), runoff is zero or extremely low on an annual basis at some locations in the basin. If this is the case, it should be regarded as a clear indication that the upstream subbasin is closed (if zero) or closing (if extremely low), even without knowing actual commitments. The relatively low runoff may have natural and human causes. Again, one should be aware of linkages in the river network, interpreting decreases in runoff with increasing downstreamness as basin closure only for locations connected through the network.

Because runoff data for the outlet of the entire river basin for which downstreamness is 100% are not available, it is impossible to conclude whether any runoff still reaches the outlet of the entire river basin (the ocean). However, because every measurement location is also the outlet of its upstream subbasin, this is not of essential importance to indicate the occurrence of the process of closure. In essence, the approach proposed in this paper allows for studying the process of closure in the subbasin upstream from any point in a river basin. The downstreamness of any point in a basin is, by definition, 100% with regard to its own catchment.

Whereas the described analyses focus on available runoff, basin closure, by definition, confronts water availability with commitments. Commitments of runoff can vary from year to year. Large differences from season to season may also exist because of spatial and temporal variability of rainfall, for example. In a basin such as the Jaguaribe basin, water withdrawals for irrigation may

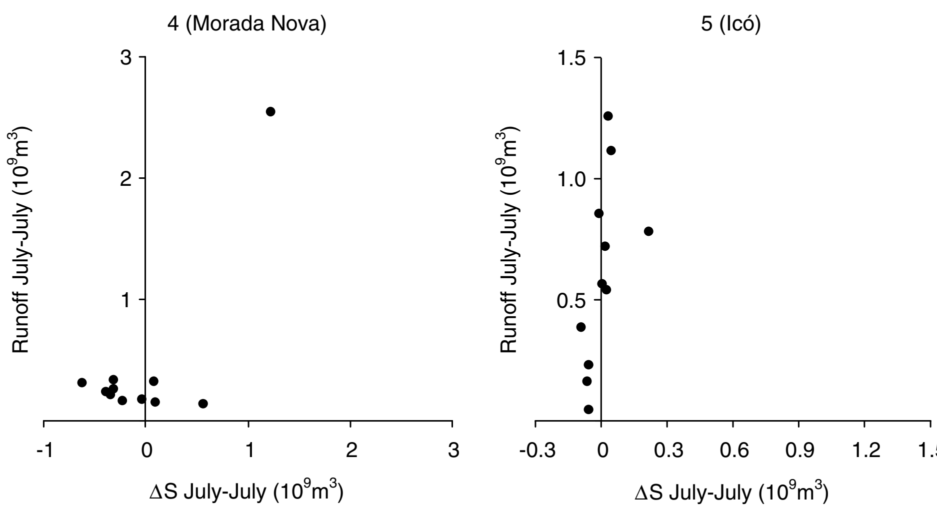

Fig. 6. Comparison of upstream storage and annual runoff at two measurement stations in the Jaguaribe Basin; change in stored volumes and runoff for annual time periods, similar to Fig. 1; storage capacity upstream of Measurement Station 4 (Morada Nova) is relatively large (see Table 1), possibly associated with major closure; the storage upstream of Measurement Station 5 (Icó) is relatively small (see Table 1), possibly associated with minor closure

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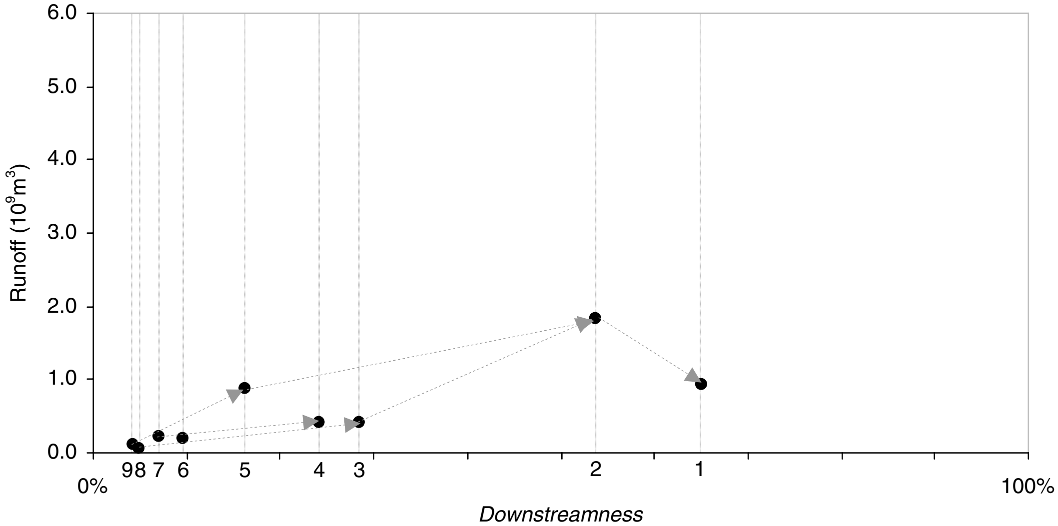

Fig. 7. Average annual runoff at selected locations 1–9 characterized by their downstreamness for 1996–2008; arrows indicate direct connections of measurement locations through the river network

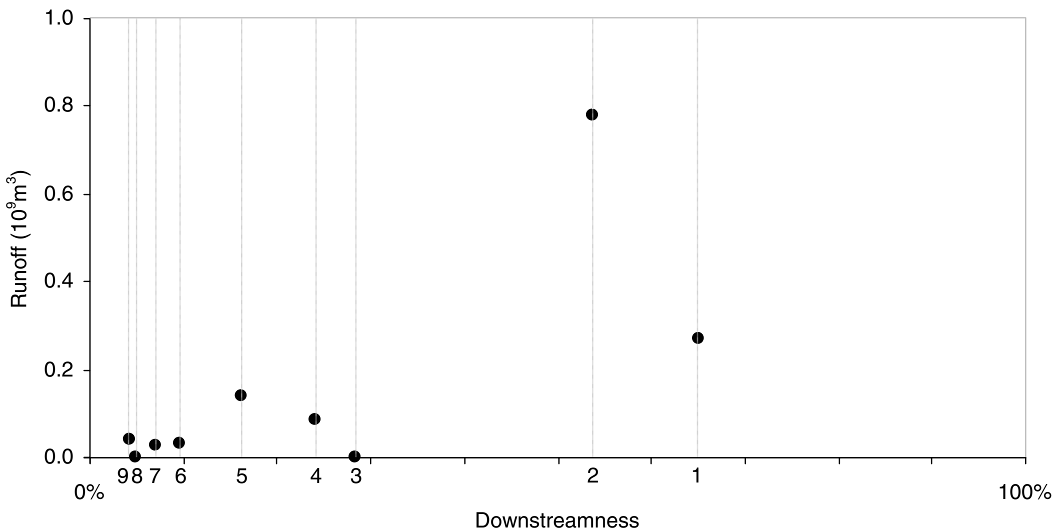

Fig. 8. Runoff in 2001 at selected locations 1–9 characterized by their downstreamness

substantially increase or decrease when the availability of water resources increases (van Oel et al. 2008).

Downstreamness of Storage Capacity and Stored Volumes in Reservoirs

Recently, storage capacity in the Jaguaribe Basin increased significantly (Fig. 9) because of the construction of the Castanhão Dam in the Alto Santo municipal district in 2002 between Measurement Stations 1 and 2. Reservoir capacity is generally underutilized even at the end of the wet season (Fig. 9). When looking at Figs. 9 and 10, one can see that decreasing stored volume can occur with decreasing downstreamness of stored volume (1998–2001) and with increasing downstreamess of stored volume (2004–2006). In the first period, downstream areas were running out of water resources faster than upstream areas were. Especially for a situation in which upstream reservoirs are designed to serve local

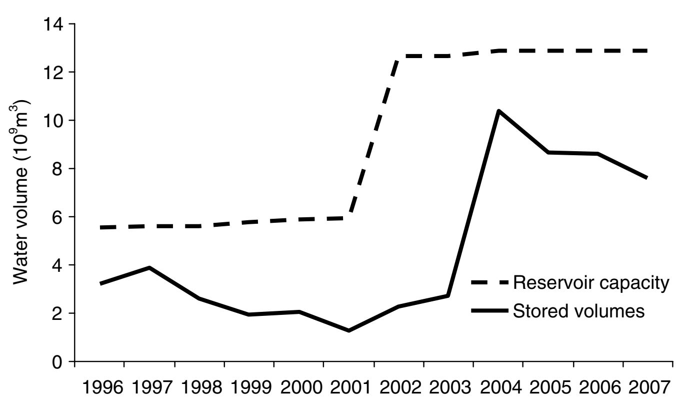

Fig. 9. Changes in reservoir capacity and actual water storage on July 1, the end of the wet season for 62 reservoirs in the Jaguaribe Basin

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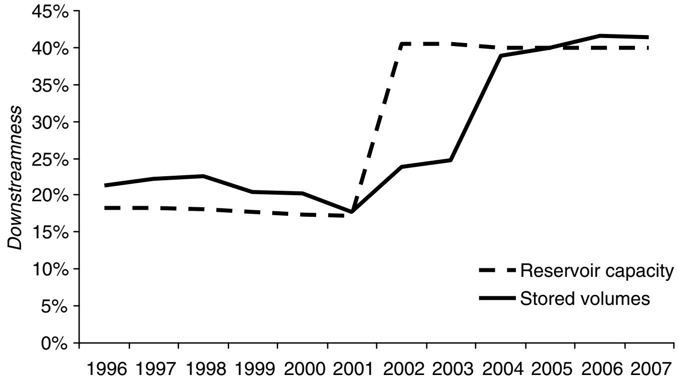

Fig. 10. Variations in the downstreamness of reservoir capacity and the downstreamness of stored volumes (July 1, 62 reservoirs) in the Jaguaribe Basin for 1996–2007

commitments, this is a clear indication of basin closure. During the period 2004–2006, the upstream parts of the basin ran out of water faster than areas in more downstream parts of the basin. This may be related to the role of Castanhão and other large downstream reservoirs that are designed to reliably store water for a few years of water demand even in the case of a series of dry years.

Projecting the downstreamness of storage allows for assessing the spatiotemporal patterns in water availability. For a comprehensive analysis of basin closure. additional analyses of actual flows and commitments are needed, along the method of analysis applied in this paper. This is, however, out of the scope of this paper.

Downstreamness of Water Demand

As is stressed in the previous sections, it is important to identify commitments for water in a basin, including environmental flow requirements [Convention on Biological Diversity (CBD) 2000; Smakhtin et al. 2004). In the Jaguaribe Basin, water demand for agriculture is by far the largest water commitment (COGERH 2003). In the municipal districts of the Jaguaribe Basin, the area used for agricultural production is primarily cultivated to produce temporal crops. On average, the area that is used for the production of temporal crops amounts to approximately 600,000 ha whereas the area for permanent crop production is limited to some 100,000 ha (IBGE 2009). Temporal crops include food crops such as rice, beans, corn, and manioc. Permanent crops include various fruits, cotton, and cashew nuts. Temporal (i.e., seasonal) crops are cultivated all over the Jaguaribe Basin, but the downstreamness of the production area dedicated to temporal crops indicates that preferential production areas are located in the upstream parts of the basin. As shown in Fig. 11, the downstreamness of the harvested area of temporal crops is between 15 and 20%. The downstreamness of the harvested area of the production area dedicated to permanent crops is approximately 50%. An important reason for the more downstream centered cultivation of permanent crops may be the need for a continuous and reliable water supply. Therefore, permanent crops more strongly rely on irrigation than seasonal crops do, most of which are grown under rain-fed conditions. The downstreamness of water demand for irrigation in the Jagauribe is hard to assess because data about irrigated areas are largely unavailable.

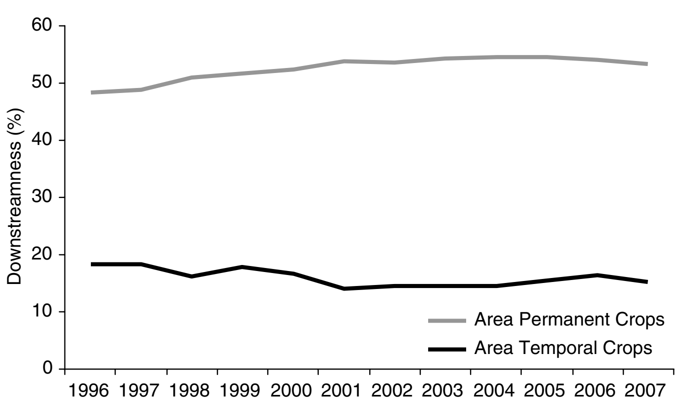

Fig. 11. Downstreamness of cultivation area for temporal and permanent crops in the Jaguaribe Basin

Discussion and Conclusion

In recent literature on basin closure, a basin is regarded closed if no water reaches the natural outlet all year around and closing if this situation is limited to part of the year (Molle et al. 2007, 2010). The phenomenon of closure has both a spatial and temporal component. Therefore, interannual variations and differences among subbasins are important and need to be considered. The concept of downstreamness and its applications described in this paper are helpful tools for depicting basin closure and identifying its drivers and consequences in space and time.

As basin closure is defined as an anthropogenic process that occurs when the development of infrastructure with a potential demand for water outstrips basin resources and ecosystem resilience (Molle et al. 2010), studies on basin closure need to be explicit about the natural and human influences on runoff. The reason for this is best explained by describing the developments with regard to runoff in the Jaguaribe Basin. Naturally, the Jaguaribe Basin is an intermittent river. This is not the effect of an anthropogenic process. By building dams, many streams have obtained a permanent flow. From a basin closure point of view, this anthropogenic intervention could be regarded as opening the basin, rather than closing it. Building dams can be effective at buffering natural variability but may invoke the overdevelopment of water resources. Measures that make sense from a local or subbasin perspective may well be counterproductive from a basin perspective. Upstream processes for closing subbasins may, for example, lead to a decrease of average downstream water availability or to an increase in the downstream variability of water availability.

River basins are generally regarded as natural units for integrated water resources management, although they could just as easily be regarded as political units (Warner et al. 2008). River basins may appear to be logical units from a supralocal perspective. However, at any geographical location within a basin, one is actually at the most downstream point of its upstream catchment. Taking this notion into account, it is argued that an infinite number of natural units for water resources management exist. For each of these units, basin closure may be a relevant management issue. If water resources are managed by local authorities or user communities, a "natural" need to cooperate with a downstream party who may claim water resources from upstream subbasins is not always present.

Water management policies rely on the valuation of the tradeoffs between the commitments of upstream and downstream uses and technical implementations of upstream and downstream measures. The concept of downstreamness can assist in analyzing subbasin points of view as an integral part of a basin perspective. In this way, the effects of anthropogenic processes driving basin closure can be better understood.

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