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A river basin as a common-pool resource: A case study for the Jaguaribe basin in Brazil

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A RIVER BASIN AS A COMMON-POOL RESOURCE:

A CASE STUDY FOR THE JAGUARIBE BASIN IN BRAZIL

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Summary

Rainfall variability and the associated water stress are of major concern in semi-arid regions subject to conflicts between water users. To achieve sustainable and stable agricultural performance it is necessary to understand the interaction between natural processes and human response. This paper investigates the applicability of common-pool resource (CPR) concepts to understand governance of water resources in semi-arid river basins. This is done by evaluating the governance of water resources in the Jaguaribe basin in the semi-arid Northeast of Brazil. The results show that common-pool resource concepts offer valuable insights for explaining variations in water resource use and availability at the river basin scale. The water system in a river basin can be characterized as one large CPR consisting of asymmetrically linked smaller CPR's. This study showed that CPR concepts are useful for explaining agricultural productivity, stability and equitability in a semi-arid river basin. The asymmetry of a river basin CPR is the cause of unidirectional externalities towards downstream. The topography, the sequence of rainfall events and distribution of reservoir capacities in a river basin strongly influence the extent to which convergence of resource flow can compensate for these externalities.

1. Introduction

Integrated river basin management includes maximizing economic, social and ecological benefits at the river basin scale. This means that solutions to particular problems should be measured against their effects on the rest of the river basin. This paper investigates the applicability of common-pool resource concepts for understanding governance of water resources in semi-arid river basins. This is done by considering the case of the Jaguaribe basin in the semi-arid Northeast of Brazil.

Governance of water resources in semi-arid Brazil is organized at the scale of a river basin and at smaller spatial scales, depending on the presence of rivers and reservoirs. The construction of reservoirs is a widely applied measure in dealing with rainfall variability. By withholding and storing water, reservoir operation aims at limiting both the mobility and variability of water resource flows. Reservoirs do not serve all water users equally well, since they serve only those in the vicinity and downstream of reservoirs.

A river basin is a freshwater resource system that can be regarded as a common-pool resource (CPR). CPR's are goods characterized by difficult and costly exclusion of users and subtractability of resource units (Ostrom, 1990). Subtractability means that the consumption by one appropriator subtracts from the possible appropriation by others. Exclusion refers to the exclusion of appropriators from using the resource. Studies on CPR's typically analyze under which conditions cooperation between appropriators does or does not emerge. Ostrom (1990; 2000) analyzed numerous case studies and sketched a theory of governance of CPR's. Attributes associated with an increased likelihood of appropriators to engage in designing and modifying governing arrangements are: (1) the feasibility of improvements; (2) the availability of reliable and valid indicators on the condition of the resource system; (3) the predictability of resource flows in the resource system; (4) the limited spatial extent of the resource system. An additional aspect is storage capacity in case of a mobile resource[1] (Schlager et al., 1994). Storage capacity is the capacity to collect and hold resource units to overcome temporal deficiencies. Storage capacity reduces the mobility of water resources.

In case of symmetrical CPR systems, like small-scale irrigation systems, there is often an institutionally feasible state that makes all the participants and the ecosystem better off (Ostrom et al., 1994). This is because appropriators face reciprocal externalities. In case of asymmetrical CPR systems, like river basins, the flowing nature of water determines unidirectional dependency among appropriators. Therefore, unidirectional externalities exist (Izquierdo et al., 2003). Unidirectional externalities in river basins are comparable to the ones experienced in canal-irrigation systems. Generally the most disadvantaged appropriators are the ones located at the downstream tail of canal-irrigation systems, most distant from the resource stock (Bardhan and Dayton-Johnson, 2002). However, a river basin forms a converging network of streams and reservoirs so that one cannot speak of a resource stock as is the case of an irrigation system with one central reservoir. This makes the system principally different from a canal-irrigation system. Convergence of flow rather than divergence takes place and potentially counterbalances the negative effects for downstream appropriators.

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[1] Resource units are either stationary or mobile, meaning that they remain spatially confined prior to harvest, or move.

2. Study area

The Jaguaribe basin is located within the institutional borders of the state of Ceará in the semi-arid northeast of Brazil. The basin covers approximately 72,000 km^2 (COGERH, 2003b). Average yearly precipitation ranges from 400 to 2000 mm. Temporal rainfall variability is highly significant on a suite of scales: inter-annual variability, seasonal variability and variability at the time scale of a week (Enfield et al., 1999; Gaiser et al., 2003; Smith and Sardeshmukh, 2000; Uvo et al., 1998). In Ceará the combination of impermeable crystalline rocks in the soil and high temperatures produces high rates of evapotranspiration and little groundwater storage. Groundwater resources are considered to be of limited importance in most areas of the basin (Johnsson and Kemper, 2005). Seventy-five percent of the basin's reservoir capacity is provided by three surface reservoirs that have transformed about 470 kilometres of the rivers in the middle and lower part of the basin into perennial waterways.

About 45% of the irrigation area in the downstream valleys is used for rice production, consuming an estimated average of 60 % of the water destined for irrigation (Lemos and de Oliveira, 2004). Rice is cultivated in both upstream and downstream areas. Irrigation for rice production is an intensively discussed practice in Ceará because of its high pressure on water reserves in strategic reservoirs (COGERH, 2001; COGERH, 2003b; Johnsson and Kemper, 2005).

Water management in Ceará is a combination of state level management with decision-making at smaller territorial scales than the river basin, such as sub-basins, regulated river valleys, and reservoirs (Johnsson and Kemper, 2005; Lemos and de Oliveira, 2004). For many CPR's in the Jaguaribe basin, User Commissions decide on the allocation of water resources from reservoirs without having an official mandate (Lemos and de Oliveira, 2004). For the largest reservoirs, most active user participation was observed.

3. Method

In three subsequent steps we analyze the physical characteristics of the river basin water resource system, current governance structures of water resources at different scales and agricultural performance (Figure 1). In a fourth step we study how the combination of the first two can explain the latter.

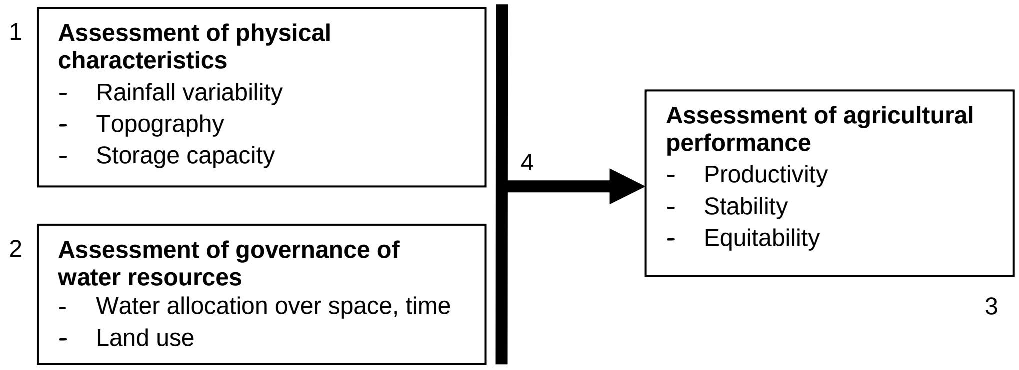

Figure 1: Research model

Step 1: Assessment of physical characteristics

Rainfall variability is analyzed for the period 1990-2004 at 80 measurement stations, one in every municipal district in the Jaguaribe basin. Yearly values for the hydrological year ($Nov_{(t-1)}$-$Nov_{(t)}$) are used. Although spatial differences are taken into account, the focus of the analysis is on the temporal variability of rainfall.

Topography determines the direction of resource flow. The size of actual flows is influenced by rainfall quantities, appropriation, evapotranspiration and storage. Every location *x* in a river basin can be characterized by the size of its upstream catchment area. If the upstream area (A_{up}) is divided by the total catchment area of the river basin (A_{tot}), a fraction is determined which we call 'downstreamness' (D_x):

$$D_x = \frac{A_{up}}{A_{tot}}$$

Water flows accumulate from up- to downstream. The direction of flow accumulation is determined using a 90 m resolution digital elevation model (EMBRAPA, 2006) of the river basin. Based on the outcome, every municipal district is categorized into either the upstream, midstream or downstream part of the Jaguaribe basin.

For analyzing storage capacity in the river basin we have considered the 58 largest reservoirs. All these reservoirs are public reservoirs, of which construction was initiated by the national or state government. The downstreamness of the total storage capacity in the river basin (D_{SC}) was determined as follows:

$$D_{SC} = \frac{\sum_{x=1}^{n} SC_x D_x}{\sum_{x=1}^{n} SC_x},$$

where D_x represents the downstreamness of reservoir *x* and SC_x the storage capacity of reservoir *x*.

Step 2: Assessment of governance of water resources

We analyze (1) water allocation over space and time and (2) land use. Water allocation is evaluated by analyzing stability of resource flows and storage over space and time. We analyze inter-annual stability of flow at eight measurement stations in three upstream sub-basins in the Jaguaribe basin. For each of the sub-basins up- and downstream flow characteristics have been compared for the period 1990-2003.

To evaluate the effect of storage the flow is compared with yearly upstream rainfall for the period 1990-2003. Intra-annual stability is determined by dividing monthly dry season flow ($Nov_{(t-1)}$-$Jun_{(t)}$) by monthly wet season flow ($Jul_{(t)}$-$Oct_{(t)}$) for the period 1990-2003. We evaluate again the differences over space.

The reservoir volumes for the 58 largest reservoirs in the basin reservoir volumes are evaluated for the period 1996-2003. The weighted average downstreamness of the total stored water volume in the basin (D_{SV}) at the end of the rainy season is compared to the weighted average downstreamness of the storage capacity in the basin.

$$D_{SV} = \frac{\sum_{x=1}^{n} SV_x D_x}{\sum_{x=1}^{n} SV_x},$$

where D_x represents the downstreamness of reservoir x and SV_x is the stored volume in reservoir x. Crop choice and the size of the production area at the municipal level are used as indicators for land use for the period 1990-2004. For the up- mid- and downstream part of the river basin the relative share of permanent (fruit) and seasonal (rice, maize, beans) crops has been determined.

Step 3: Assessment of agricultural performance

To measure agricultural performance in the basin three indicators are used following Conway (1987). This is done for 80 municipal districts in the river basin. The three indicators of agricultural performance are:

- Productivity: productivity is the average yearly value generated per hectare in a district. To unify the output of various agricultural products, their monetary value is used. This value is based on average prices per agricultural product in the period 1994-2004 (IBGE, 2006).
- Stability S of production: the variation of production over time (1990-2004). Use is made of the coefficient of variance (CV). Stability is defined as: $S = 1/CV$.
- Equitability E of productivity and stability over space. Use is made of the Gini coefficient (Gini, 1912) for which the agricultural incomes from seasonal crops of the 80 municipal districts in the basin are taken into account. Equitability is defined as: $E = 1 - gini$, with $0 \leq gini \leq 1$.

The focus of the performance analysis is on the main seasonal crops cultivated in the basin (rice, maize and beans). This choice has been made because decision-making with respect to cultivating these crops is done on a seasonal basis and consequently, inter-annual variation of water consumption per hectare is only limited. Trade-offs between productivity, stability and equitability are identified.

Step 4: Synthesis: human-environment interactions

Physical conditions (step 1) and governance of water resources (step 2) are related to one another. Storage capacity is a result of governance responding to rainfall variability. Water allocation over space and time is partly governed by human intervention, but also determined by the physical conditions and land use. Similarly, land use is influenced by a combination of physical conditions and water allocation. In this step we relate the first two steps to agricultural performance (step 3).

We interpret the physical characteristics of a semi-arid river basin, such as the Jaguaribe basin, in terms of CPR characteristics. We will assess whether and where cooperative governance is likely for this resource system from a theoretical perspective. We compare the expectations based on theory with our observations in the field.

Use is made of agricultural production data (IBGE, 2006), rainfall data (FUNCEME, 2006), a digital elevation model (EMBRAPA, 2006), a database on reservoir volumes and releases from the Brazilian National Department of Works Against Droughts (DNOCS) and the Ceará state department for water resources management (COGERH, 2003a) and river flow data from the Brazilian National Water Agency (ANA, 2006).

4. Results

4.1 Assessment of physical conditions

The 'downstreamness' of locations within the river basin is shown in Figure 2, first on grid level (left figure) and then on district level (right figure). The downstreamness has been classified into three categories: upstream, midstream and downstream. The downstreamness of a district as a whole is measured at its most downstream point.

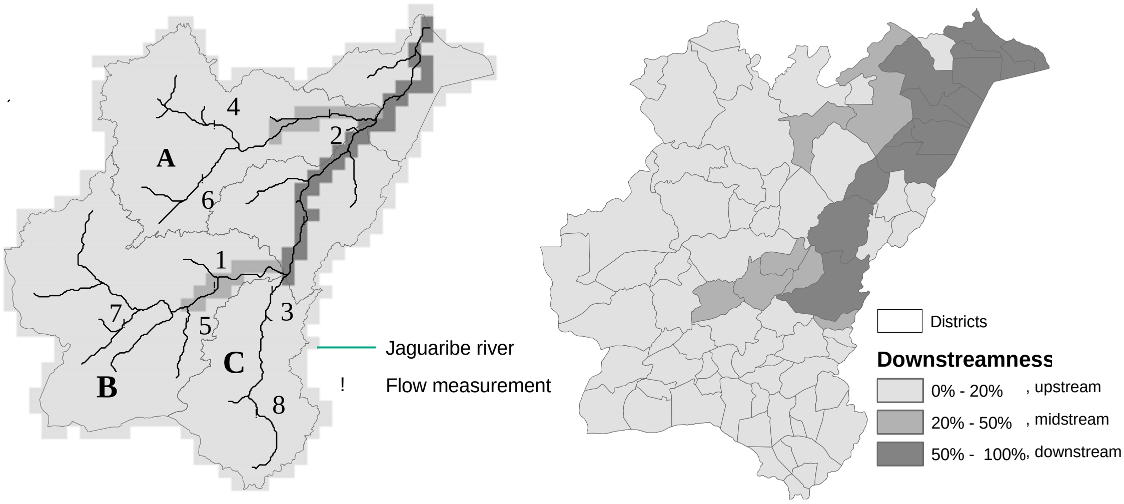

Figure 2: Left: Stations for flow measurement in the Jaguaribe basin. Sub-basins are indicated with A (Banabuiú), B (Alto Jaguaribe) and C (Salgado). Right: All 80 districts in the basin have been categorized as either up-, mid- or downstream.

River basin scale authorities and local communities adapt to rainfall variability by constructing reservoirs. In the Jaguaribe basin this process of adaptation is ongoing (Figure 3) and makes water resources less mobile at local scales. New local CPR's produce externalities for downstream appropriators. The capacity-weighted downstreamness of the basin's storage capacity (D_{SC}) has shown a decreasing trend after the installation a large reservoir in 1961 (Figure 3). This trend continued until the installation of the large Castanhão reservoir in 2003 (COGERH, 2003a). Due to the additional installation of smaller, private reservoirs the downstreamness is even lower, since small reservoirs are generally located in the most upstream parts of the river basin. However, no quantitative data on this development were available.

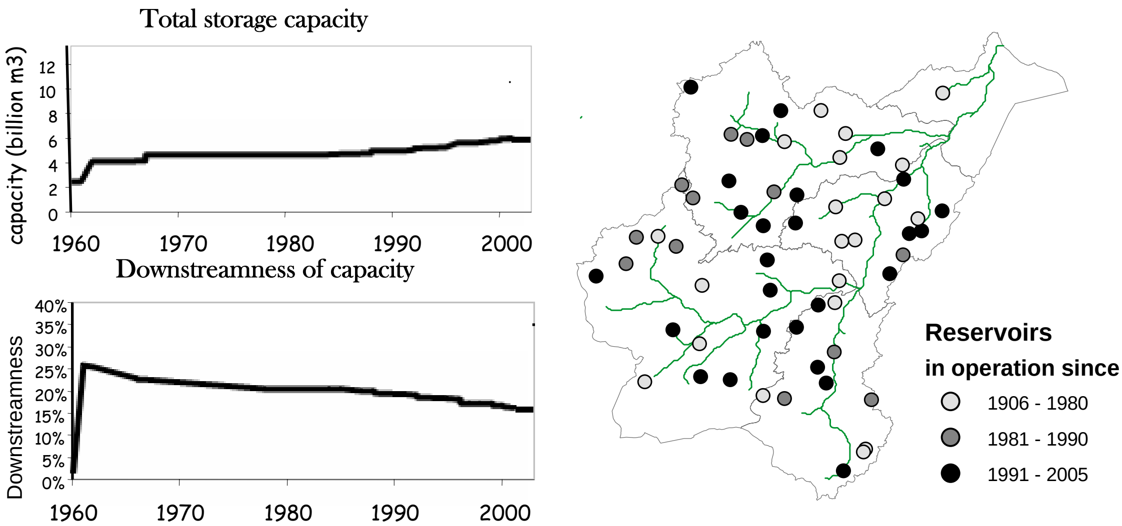

Figure 3: Left: decrease of downstreamness of total strategic storage (D_{SC}) in the Jaguaribe basin. Right: locations of public reservoirs in the Jaguaribe basin

4.2 Assessment of governance of water resources

4.2.1 Water allocation over space and time

Intuitively, more intense rainfall should yield higher yearly discharges at the outlet of a sub-basin, since terrain conditions remain largely unchanged[2]. Differences from this trend should be explained by inter-annual effects, largely related to storage. The 1993 drought seriously affected discharges in 1994 in all three sub-basins. The amount of rain in 1994 would have resulted in a higher discharge if it wasn't for the 1993 drought. Most probably, saturation of natural and artificial storage bodies upstream of the measurement stations took up a large part of the 1994 rains.

In sub-basins A, B and C inter-annual stability of river discharge increases in the downstream direction (Figure 4). This holds most strongly for sub-basin A, where a large strategic reservoir is operated to serve the downstream community, mainly consisting of irrigation farmers[3] downstream of measurement station 2.

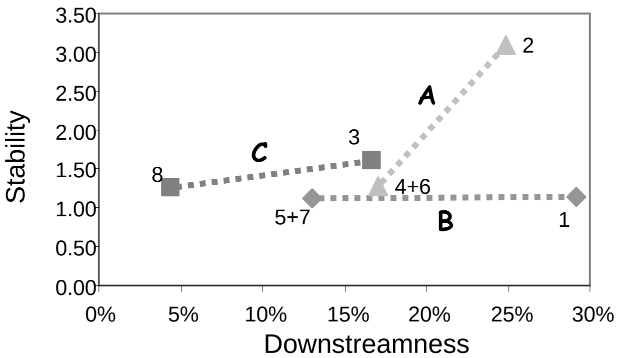

Figure 4: Stability (1/CV) of flow in three upstream sub-basins. A = Banabuiú sub-basin; B = Alto Jaguaribe sub-basin; C = Salgado sub-basin. 1-8 represent discharge measuring stations.

[2] Evaporation and water consumption are expected to increase in dry periods, resulting in even lower downstream discharges in years with the lowest rainfall values.

[3] Among which is the public irrigation scheme of Morada Nova, the largest of its kind in the Jaguaribe river basin. In this irrigation scheme, 85% of the irrigated area is used for rice production.

Reservoir management in sub-basin A is much more successful in stabilizing river flow than it is in the other sub-basins. The average flow is however considerably lower than in the other two sub-basins. The characteristics of flow for the three sub-basins are summarized in Table 1.

The variance of flow decreases with a higher level of upstream storage capacity. The rate at which the variance of flow decreases in the downstream direction increases with the level of upstream storage capacity. However, the low variance of flow is accompanied by a relatively low average discharge.

Table 1: Discharge characteristics of three upstream sub-basins.

Variable	Unit	A	B	C
Catchment size	km^2	17 900	21 000	12 000
Reservoir capacity	10^3 m^3 / km^2	154	16	37
$\frac{Q(dryseason)}{Q(rainyseason)}$	-	0.86	0.01	0.03
Annual variance of discharge	Coefficient of variance	0.32	0.88	0.62
Average downstream discharge	10^6 m^3/year	257	312	410
Rainfall	mm/year	752	703	862

The basin's storage capacity slightly increased in the period between 1996 and 2003, while total stored volume decreased (Figure 5). In Figure 6, the average capacity-weighted downstreamness of storage capacity (D_{SC}) and the average volume-weighted downstreamness of stored volume (D_{SV}) are shown.

In the dry year of 1998, total stored volume dropped, while the downstreamness of stored volume (D_{SV}) increased. This can be explained by the fact that multi-annual storage is easier achieved in relative downstream parts of the river basin. However, in the dry year of 2001, downstream stored volumes decreased faster than upstream stored volumes. In the years following 2001, total stored volume rose again while the downstreamness of stored volume (D_{SV}) decreased further and consequently the situation with $D_{SC}>D_{SV}$ remained. For a period of three years (2001-2003) a situation with upstream above-proportional storage (appropriation) was observed. This is explained by the saturation level of the reservoir network in this period. With an increasing share of storage capacity left unsaturated following a drought, the downstreamness of stored volume (D_{SV}) moves upstream, provided that rainfall rates will not be extremely high. This implies that upstream storage recovers faster after a drought than downstream storage. The sequence of rainfall events is very important for the spatial allocation of water quantities. Responsible for the effects of the sequence of rainfall events are the 'funnel effect' and the 'storage effect' (Table 2). The 'funnel effect' refers to the accumulation of flow in the downstream direction. The storage effect refers to the storage of water in surface reservoirs and favours the water users that are first in line, i.e. the upstream users.

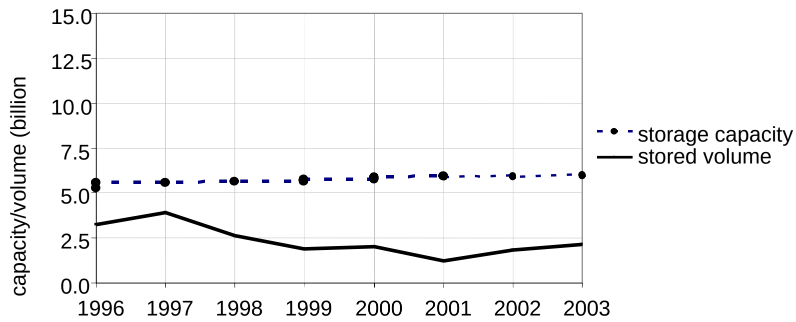

Figure 5: Storage capacity and stored volume in the Jaguaribe river basin

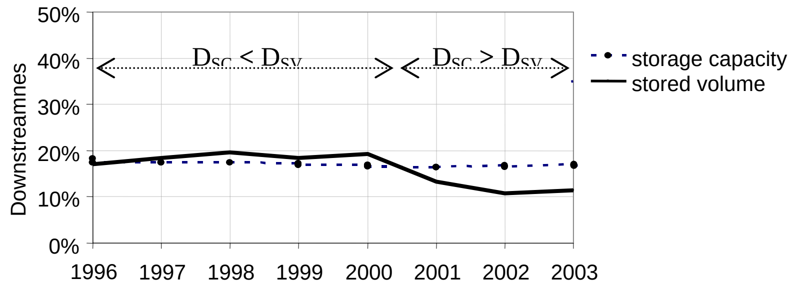

Figure 6: Volume-averaged location of total storage capacity and stored volume (1st of July)

Table 2: The influence of the 'funnel effect' and the 'storage effect' over time.

Process	Effect on users	Wet following wet year	Wet following dry year	Dry following wet year	Dry following dry year
Funnel effect of flow accumulation	Outlet-advantage for downstream water users	++++	+++	++	+
Storage effect	First-in-line-advantage for upstream water users	+	++	+++	++++

4.2.2 Land use

Recently a change in land use has taken place, with permanent crops being more concentrated in downstream parts of the river basin. In the period 1990-2004 fruit production in the downstream part of the basin increased from around 2 to 13 per cent of the total production area.

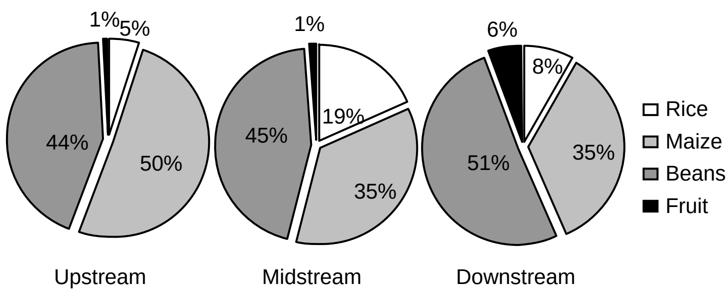

Figure 7: Area share of individual crops (average 1990-2004)

The relative high stability of water supply in the midstream part of the basin does not cause farmers to choose for more permanent crops in comparison to farmers in the upstream part (Figure 7). The municipal districts where measurement stations 2 and 3 are located[4] do not contain a larger fruit area than the municipal districts upstream. The fruit area increased dramatically in downstream areas. This resulted in a higher permanent water demand, bringing along the risk of high loss of income in case of water failure.

Table 3: Water consumption and yield in the Jaguaribe basin (COGERH, 2003b).

Crop	Water requirement (m^3/ha/year)	Production value ($R/ha/year)
Rice	33.000	4.500
Fruit	20.000	12.00
Maize	18.500	1.600
Beans	14.500	2.300

The information in Table 3 implies that the midstream zone has the highest water use pattern, followed by the downstream zone and that most revenue is achieved in the downstream zone followed by the midstream zone.

Downstream land use is strongly influenced by reservoir operation. Downstream of the two largest public storage reservoirs a significant positive linear relation between reservoir release and production area was found (Figure 8).

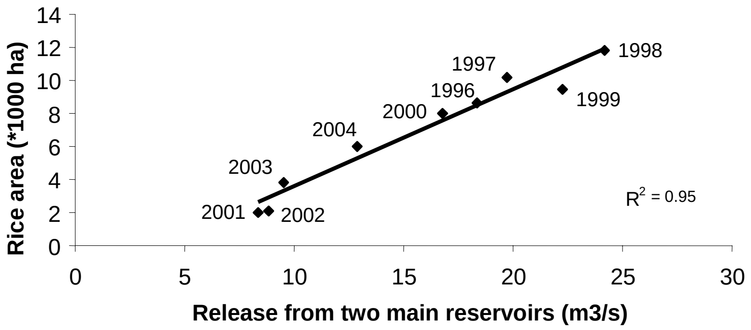

Figure 8: Downstream rice production area for average dry season reservoir releases

4.3 Assessment of agricultural performance

4.3.1 Agricultural productivity and stability

For municipal districts in the upstream part of the river basin, there is a significant positive linear relation between rainfall and agricultural productivity. In mid- and downstream districts no such relationship was found. Districts in the midstream zone have the highest productivity and the most stable production (Table 4).

[4] These are the districts of Morada Nova and Icó, the two municipal districts where two large public irrigation schemes are located.

Table 4: Productivity and stability of production of seasonal crops (rice, beans, and maize) for the period 1990-2003.

Zone	Productivity ($R/ha)	Stability of production (1/coefficient of variance)
Downstream	370	2.9
Midstream	520	4.0
Upstream	200	1.9
Basin total	240	2.4

4.3.2 Agricultural equitability

In Table 4 the distribution of productivity and stability of production over the three parts in the Jaguaribe basin is shown. Both for productivity and stability of production the same pattern has been encountered. Appropriators in the midstream zone were most successful. They have taken advantage of their relative downstream position with respect to the districts in the upstream zone. This is of great importance in order to cope with short-term intra-season rainfall variability and to be productive in the dry season. In dry periods, appropriators in the midstream zone experience the advantage of first access to water from large reservoirs.

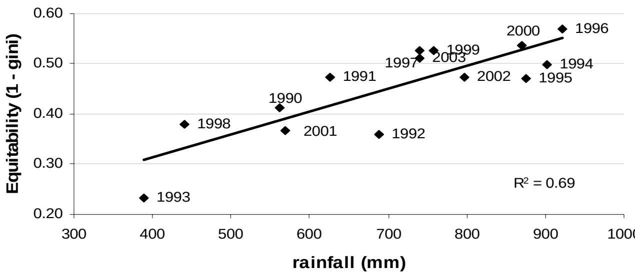

Figure 9: Equitability (1 – gini-coefficient) of produced value in the Jaguaribe basin as a function of average rainfall.

Equitability of agricultural productivity is influenced by physical conditions and governance in the river basin. The average yearly rainfall in the river basin has a (95%) significant linear positive relation with equitability (Figure 9). The spatial distribution of agricultural production over the river basin becomes clear when the gini-coefficient of seasonal crop value for all 80 districts is compared to the actual locations in the river basin where the agricultural production is established. Decreasing equitability comes with a more downstream-centred total production value.

4.4 Trade-offs between productivity, stability and equitability

The following trade-offs between productivity, stability and equitability have been encountered:

1. Highest equitability conflicts with overall stability. Stable flows are best achieved in mid- and downstream parts of the river basin. For higher equitability, reservoir capacity must be distributed spatially more homogeneous. This implies additional small reservoirs in upstream parts of the river basin. This will result in less stable flows at the river basin scale, due to higher evaporation and increasing upstream appropriation. A consequence is faster resource exploitation in case of meteorological drought. The effects of meteorological drought will also last longer due to unsaturated upstream reservoir capacity following meteorological drought. Evidence for this to already take place in the Jaguaribe river basin are the unequal saturation levels of storage capacity in the aftermath of the 2001 drought shown in Figure 6. The effect of this would be an increasing agricultural production in times with good meteorological conditions, especially in upstream parts of the river basin, and decreasing agricultural production in times of meteorological drought.

2. Highest productivity conflicts with stability. Highest productivity is achieved with crops that generate highest revenues per unit of water. These crops are generally perennial (permanent) crops. Perennial crops require inter- and intra annual stability of water supply. Cultivation of perennial crops in the Jaguaribe river basin is increasing. Large scale cultivation of perennial crops attempts to profit optimally from available stable flow, but in doing so it increases the risk of high damage in case of serious drought, when flow decreases. This conflicts with stability of production. Furthermore, for stabilizing production, a stable water resource flow should be provided. This means a conservative reservoir operation strategy, and a consequent lower average discharge. Lower average discharges result in lower production values.
3. Highest productivity conflicts with equitability. Highest productivity is achieved with permanent crops. These crops need stable resource flows for irrigation. Since flow stability is heterogeneously distributed over the river basin (Figure 4), this can only be achieved in limited parts of a river basin. This goes at the expense of equitability.
4. Maximizing local productivity undermines river basin scale productivity. For upstream regions, highest productivity is achieved by efficient use of water resources in the short term. Within-wet-season deficiencies are overcome with local storage. As water availability in upstream parts is not stable enough for large-scale cultivation of permanent crops, most suitable are seasonal crops with relatively low added value per unit of water. By passing on appropriation externalities to downstream communities, upstream appropriators undermine water resources to reach downstream appropriators. This leads to sub optimal results in the part of the river basin that was originally best suitable for generating the highest revenues per unit of water. Clear proof is the difference in average production and the variance of production of seasonal crops between the mid- and downstream zone. Farmers in districts in the mid-stream zone achieve much better results than farmers in the downstream zone (Table 4).

4.5 Synthesis: human-environment interactions

Certain attributes of a resource are associated with an increased likelihood of appropriators to engage in designing and modifying governing arrangements (Ostrom, 2000):

1. **Possibility of feasible improvements**: resource conditions are not at a point of deterioration such that it is useless to organize or so underutilized that little advantage results from organizing.
2. **Availability of reliable and valid indicators**: indicators of the condition of the resource system are frequently available at a relatively low cost.
3. **Predictability of resource flows**.
4. **Limited spatial extent:** the resource system is sufficiently small, given the transportation and communication technology in use, for appropriators to develop accurate knowledge of external boundaries and internal microenvironments.

Table 5 shows how these attributes can be found in semi-arid river basins and how these attributes manifest for CPR’s in the up-and downstream parts of a river basin.

Table 5: CPR attributes in favour of cooperative governance in semi-arid river basins.

CPR attributes in favour of cooperation	River basin CPR		Upstream CPR's		Downstream CPR's	
1. Possibility of feasible improvements	Appropriation and rainfall dependent	+	Rainfall dependent	-	Appropriation and rainfall dependent	+
2. Availability of reliable and valid indicators	Spatially scattered	+/-	Good measurements difficult	-	Efficient measurements rainfall, runoff and storage	+
3. Predictability of resource flows	Spatially scattered	+/-	Rainfall predictions insufficient	-	Crude rainfall and runoff predictions possible	+
4. Limited spatial extent	Too large	--	Small	+	Large	-

We distinguish between a spatial and temporal dimension for the way a river basin resource system facilitates cooperative governance. The temporal dimension relates to temporal rainfall variability. The inter-annual sequence of rainfall events is of critical importance for the feasibility of improvements by cooperative governance in a river basin. Forced by topography, most rainfall precipitates in relative upstream parts of a river basin. During drought, downstream water demand increases while upstream reservoir capacity remains unsaturated. In effect, the negative effects of meteorological drought last longer in downstream parts of the river basin. Following meteorological drought a relative large share of rainfall volumes will be extracted from the resource system in order to saturate upstream reservoir capacity. This process can be interpreted as above-average appropriation by upstream appropriators.

The spatial dimension relates to the spatial heterogeneity in a river basin, with respect to topography and storage capacity. The topography of a river basin determines to a large extent the heterogeneity in access to water resources. The spatial extent of CPR's, both the size of reservoirs and of its demand area, increases in the downstream direction. The availability of reliable and valid indicators and the predictability of resource flow increases in the downstream direction due to the delay between rainfall and river flow together with knowledge on upstream storage of water resources. We discuss the implications of these spatial differences for the river basin scale and embedded CPR's in upstream and downstream parts of the river basin.

The Jaguaribe river basin is a resource system that is composed of numerous linked CPR's. The river basin can be regarded as one large CPR, where communities governing local CPR's are appropriators and local storage is appropriation. The presence and location of reservoirs and the extent to which the reservoir capacity is saturated play an important role in the propagation of externalities. An increase in reservoir capacity due to the construction of additional reservoirs in upstream parts of the river basin increases the potential for producing negative appropriation externalities. There are many individual appropriators in the river basin, using water resources of which it is not clear to which local CPR it belongs. Examples of these appropriators are the ones using rainfall water or water from rain fed streams and rivers. These appropriators influence the resource system but do not have the possibility to take part in cooperative storage strategies. For these upstream appropriators no feasible improvements of cooperation are possible.

Upstream CPR's are small scale reservoirs or groundwater basins. Governance arrangements could involve water allocation and strategies for multi-year storage. Rainfall variability seriously influences the feasibility of improvements and the predictability of resources flows. Multi-year storage is relatively difficult to achieve in upstream parts of a river basin for two reasons. Firstly, storage in small reservoirs is generally less efficient than in larger reservoirs. Secondly, appropriators with a relative short time horizon[5] typically adopt strategies which yield more immediate results, and disregard longer-term considerations in resource conservation (Baland and Platteau, 1999). Generally, upstream governance can be associated with 'use it or lose it' strategies. Obviously this reduces the feasibility of improvement (of flow stability) by cooperation at the multi-year scale.

Upstream CPR's produce negative externalities for larger CPR's downstream. This influences flow quantities and flow stability. Multi-year storage is possible as large quantities of water can be stored more efficiently than in upstream parts of the river basin. This possibility increases the feasibility of improvement by cooperation. Since downstream CPR's depend on river discharges next to rainfall for their resource flow, indicators are more reliable as well. This is closely related to the higher predictability that downstream CPR's experience.

Appropriators in between of the upstream and downstream parts of the river basin experience the relative advantage of the accumulation of upstream water resources. In addition they experience the relative advantage of being at the head-end of the largest storage reservoirs. The result of this might be relative high agricultural performance in the midstream part of the Jaguaribe river basin (Table 4). Interestingly the largest incentives towards participation in water allocation from reservoirs have been observed in the downstream part of the basin (Table 6).

We believe it is useful to keep in mind CPR concepts when dealing with river basin management in semi-arid regions. This can be done by regarding the river basin as a resource system of linked CPR's related by the topographical features of the river basin. Between these CPR's externalities are directed downstream and are influenced by both appropriation and rainfall variability. The river basin can also be regarded as a larger asymmetrical CPR in which private appropriators and local CPR communities act as individual appropriators. A river basin is composed out of an infinite amount of sub-basins. With the installation of reservoirs local CPR's are created. The scale at which cooperative governance can take place depends, among other things, on the four attributes in Table 5. These attributes are related to the topographical features (downstreamness and presence of reservoirs) of the river basin and rainfall variability (Figure 10).

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[5] Time horizons are related to distribution of wealth. Poor users are not willing to undertake conservation investments or endure present sacrifices in the form of self-restraint in the use of the resource even though such actions would increase their future permanent income (Baland and Plateau, 1999). In remote upstream parts of the Jaguaribe river basin generally the less wealthy users are encountered.

Table 6: Differences between three topographical zones in the Jaguaribe river basin.

Location	Attribute effect: Feasible improvement (of flow stability)	Availability of reliable and valid Indicators	Predictability	Limited spatial extent	Total	Observed organization activity at the scale of individual CPR	Observed agricultural performance
Upstream	-	-	-	+	-	-	Productivity: - Stability: -
Midstream	+/-	+/-	+/-	+/-	+/-	+/-	Productivity: + Stability: +
Downstream	+	+	+	-	+	+	Productivity: +/- Stability: +/-

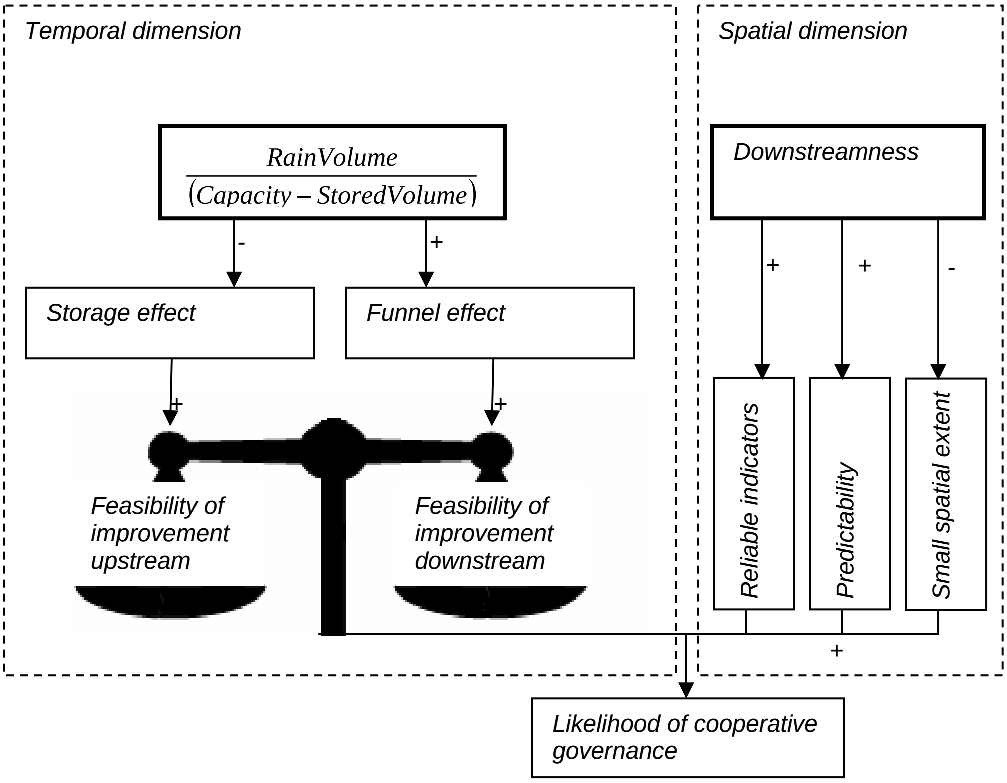

Figure 10: Likelihood of cooperative governance in a semi-arid river basin as a function of rainfall and downstreamness..

5. Discussion

A resource system like a river basin could be regarded as a network of local CPR's, where externalities are unidirectional in the downstream direction and where rainfall variability plays an important role in the extent to which these externalities manifest over time.

The asymmetry does not necessarily mean that there are no possibilities for cooperation that is beneficiary for both up- and downstream appropriators. We disagree with the notion that a river basin should be regarded as a sequential chain of private goods without reciprocal externalities (Izquierdo et al., 2003). The drainage process in a river basin is rather convergence than sequence. The converging nature of resource flow in river basins enables for more efficient storage downstream. This can make upstream appropriators depend on downstream production in times of meteorological drought. The fact that local maximum productivity can take place at different meteorological moments in time generates opportunities for governance arrangements. To effectively persuade upstream appropriators to limit their storage, some form of compensation should be offered to upstream appropriators for not using/storing water at certain moments.

Although not explicitly taken into account here, attributes of appropriators are important for the level of cooperative governance as well. Among these attributes are appropriators' dependency on the resource; their autonomy and organizational experience, reciprocity in their relations and income heterogeneity. Income heterogeneity was observed at the river basin scale (Table 4). In literature equality of income is used to explain the success or failure of CPR management (Jones, 2004). Either very high or very low levels of inequality are argued to facilitate for successful resource management. Changing inequality redistributes incentives and has therefore an ambiguous effect on the ability of appropriators to take steps toward conserving their resources and even toward setting up the required mechanisms (Baland and Platteau, 1999). In the case of the Jaguaribe basin the inequality is considerably variable over space and time. The results show that income inequality relates both to rainfall variability and governance of water resources. This makes it very complex to determine the influence of income inequality on governance of water resources and vice versa.

To some extent, data availability limited the extent to which system dynamics could be isolated from their environment. Firstly, the spatial resolution of analyzed data is too coarse for the analysis of most of the local CPR's. Only the size of CPR's that are organized around the largest water resource storage bodies is larger than the size of a single municipal district. Even than, the resolution of the data does not allow for spatial explicit analysis of individual CPR's. 'Choices over scale, extent, and resolution critically affect the type of patterns that will be observed, because patterns that appear at one level of resolution or extent may be lost at lower or higher levels' (Gibson et al., 2000). Finer resolutions can be achieved by using remotely sensed imagery classification methods. An attempt to use such an approach is in progress. Secondly, the temporal resolution of one year does not allow for considering seasonal differences in appropriation of water resources. Differences in timing on the agricultural calendar are believed to be of critical importance for understanding the process of propagation of externalities between local CPR's in the downstream direction. Thirdly the temporal extent of the analysis is limited. Only a limited amount of meteorological events occurred. In addition, the sequence of meteorological events has proven to be very important, since externalities occur on an inter-annual scale. Fourthly, the single-case method limits the general applicability of this analysis. However, within the case of the entire basin it has proven to be possible to compare the results of sub-basins.

6. Conclusion

Common-pool resource concepts can be useful for understanding governance of water resources in semi-arid river basins confronted with uncertain rainfall variations. This study shows that CPR attributes are useful for explaining spatial heterogeneity of agricultural productivity and stability in a semi-arid river basin. The asymmetry of a river basin CPR is the cause of appropriation externalities to be unidirectional towards downstream. The sequence of rainfall events and the reservoir capacity in a river basin strongly influence the extent to which convergence of resource flow can compensate for these externalities.

Reservoirs serve stability of water availability for appropriators located in the vicinity or directly downstream. It was observed that controlled outflow for local use conflicts with interests of communities further downstream. This principle is an additional concept to head-end/tail-end problems encountered in irrigation schemes (Bardhan and Dayton-Johnson, 2002), now observed at the river basin scale. Two counter effective processes clarify this principle: (1) flow convergence in the downstream direction (‘funnel effect’); (2) saturation of storage capacity in the river basin (‘storage effect’). These processes are not equally influential over time. The extent of their effect depends greatly on reservoir capacity, extraction of water resources, rainfall quantities and the sequence of these from year to year. The outcome of these processes is a landscape of water availability that changes constantly over space and time. This implies a rainfall- and appropriation dependency of the feasibility of improvements by cooperative governance.

When upstream communities increase their storage capacity, spatial differences related to mobility of water resources on the river basin scale are partly overcome. In this way an increase of equitability is achieved. From a river basins’ perspective, local storage upstream can be associated with ‘first capture’ or ‘use it or lose it’ strategies. This is in conflict with the notion that these strategies are associated with mobile flows, lacking storage capacity (Blomquist et al., 1994; Schlager et al., 1994). Upstream storage in semi-arid river basins should therefore be regarded as appropriation from the ‘river basin scale common-pool resource’, since local storage is stored for local use.

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