Scale issues in the governance of water storage projects

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Abstract

In the face of growing demands for water and supplies that are likely to become more variable and less reliable, equitable sharing of water will require a steadily increasing physical capacity to store water. This is especially true for sub-Saharan Africa but is also relevant for many other parts of the developing world. It is subject of debate whether such storage capacity should be centralised in the form of conventional large reservoirs and large-scale interbasin water transfer schemes such as those being developed in China, India, South Africa and the United States, or de-centralised and distributed in the farmers' fields, and at the scale of the micro-watershed and village (tanks, micro-dams and aquifers). The policy choice between developing centralised or distributed water storage is an important one, and requires critical analysis. The institutional dynamics of building a centralised storage system that is consistent with IWRM principles is very different from the institutional dynamics of supporting multiple local and regional endeavours to deal with the problem. The paper explores conceptually how this policy choice could be addressed in poor countries and especially in relation to agricultural water needs. It proposes four criteria for choosing between these two scalar options.

Keywords: global change, scale, storage, water management

1. Introduction

Global fresh water supplies are limited and water availability varies largely in space and time. Many people still lack reliable access to adequate amounts of fresh water of sufficient quality for domestic and productive purposes (UN, 2005; WWAP, 2006). Their access is constrained by the natural spatial and temporal variability of rainfall and river flow, which is likely to be further jeopardised because of the impacts of climate change (IPPC -1, 2007). Rising population levels, sustained positive economic growth rates in many countries, strong urbanization trends and recent calls for increased production of biofuels are likely to significantly increase the demand for water. This obviously will add to the pressures on water resources in water stressed regions of the world (UNDP, 2007). While water use in excess of natural supply on an annual basis at present is limited to very small although densely populated regions of the world, the seasonal challenges facing humans is much higher (WWAP, 2006: 2). In many places of the world water availability is highly variable over time. Whereas on average sufficient water may be available, periods of excess are followed by periods of deficit. Shortages of water have not only direct impacts on domestic requirements but also on food production and other productive uses of water, whereby often food production is the largest water consumer. Greater rainfall variability is thus correlated with lower per capita GDP (Brown and Lall, 2006). Water storage is required to buffer livelihoods and insure families, communities and societies against shortages. Such stores of water transport water in time, from periods of excess to periods of deficit (Keller et al., 2000; Grey and Sadoff, 2006) and in space from places of water excess to places of water deficit.

There is thus a need for innovative solutions to ensure water security on a day to day basis on a large-scale and especially within the developing world. While in the 1960s and 1970s the focus of development cooperation was on infrastructure development as the key to promoting development in the developing countries, this was followed by a focus on changing policies and governance patterns in the 1990s (Meier, 2001; Wuyts, 2002; Pronk, 2001, 2003). In the water field this implied a shift from emphasis on dams and large hydraulic works to an emphasis on improved water management, enhanced allocative efficiencies and increased water use efficiencies in the 1980s and 1990s (Pahl-Wostl, 2002; 2007). It is increasingly being realised that the latter focus is necessary but not sufficient to fundamentally address the water challenge. The “soft” interventions of the 1990s need to be complemented by “hard” interventions that aim at augmenting the buffering capacity of water systems against increasing seasonal and annual variations in water availability. It is not enough for integrated water resources management strategies to only focus on improving the water management “processes”; it is also required to implement (bio-) physical interventions in terms of increasing the capacity to store water volumes. This will enable households, communities and societies to effectively cope with the seasonal and annual variation in fresh water supplies and enhance the resilience of their water systems to climate shocks (Koudstaal et al., 1992; Savenije and Van der Zaag, 2000; Shah and Van Koppen, 2006; Grey and Sadoff, 2006; Moench and Stapleton, 2007). This may form a “tipping point” that will enable rural people to lift themselves out of the poverty trap (Swallow et al., 2006). Although, it is correct to acknowledge that if good processes are in place, good choices are likely to be made, this paper attempts to contribute to the identification of some criteria that will help policymakers may such choices.

It is unclear whether additional storage capacity should be centralised in the form of conventional large reservoirs and large-scale interbasin water transfer schemes, or de-centralised and distributed in the farmers’ fields and at the scale of the micro-watershed and village or some permutation or combination of these two extremes. The policy choice between developing centralised and distributed water storage therefore requires critical analysis.

This paper does not question whether additional storage capacity is required but rather what types. It acknowledges that water buffers can take different shapes and forms and that biophysical interventions normally have non-physical ramifications, including social consequences and implications for governance. The paper hypothesizes that these non-physical implications are likely to be non-linearly related to the size of the storage facility. The paper thus investigates from a governance perspective what the preferred storage options are: many small-scale storage reservoirs distributed in the landscape or fewer larger-scale reservoirs that are more centrally managed, or combinations thereof.

The focus of this paper is on meeting primarily agricultural needs of rural populations in especially poor countries. As a result, some of the considerations that will affect decision making in richer countries have not been explicitly focused on, rather the focus is on the primary indicators needed for developing countries to make critical choices. These include cost-effectiveness and economies of scale.

This paper first briefly introduces some basic aspects of water storage. It then provides a theoretical discussion of issues of scale from a natural science and a social science perspective. The purpose of this discussion is to elicit criteria for evaluating technical options. It then discusses small and large scale storage options and the complementary institutional structure needed to deal with this. It then assesses these options and draws conclusions.

2. Water storage

Before moving further it is relevant to briefly list the various storage options that are available. Table 1 provides an overview of different types of water storage, by distinguishing the source of water (capturing rainfall directly, or capturing surface water) and the medium of storage (a container like a tank or a surface reservoir, the unsaturated zone of the soil (the upper layer of the soil), and the saturated zone (deeper underground in aquifers)).

Table 1: Different types of water storage

Water source / Storage medium	Rainfall	Surface water
Unsaturated zone	Rainwater harvesting through plant spacing, ploughing along the contour, ridges and bunds, and terracing	Runoff harvesting from adjacent uncultivated plots, compound areas, roofs and roads directly unto cropped fields
Saturated zone	Aquifer storage of seepage “losses” from impoundments	Aquifer storage from artificial recharge Sand dams
Container	Runoff harvesting from adjacent uncultivated plots, compound areas, roofs and roads into a pond, tank, or reservoir; roof-top harvesting is an option being promoted in urban and semi-urban areas	Impounding river flow in small, medium and large reservoirs, both in-stream and off-channel

The type of water use (domestic, animal husbandry, arable agriculture, and other productive purposes such as for industry, cooling water for energy installations, and the service sector) is frequently related to the source of water and the medium of storage, such as rainwater harvesting to enhance soil moisture (agriculture), and collection of water from rooftops (domestic). Although domestic water use is the most vital and often given the highest priority, it requires relatively small amounts. By far the largest water user in most rural settings is agriculture. This paper will therefore mostly focus on agricultural water use, with the understanding that stored water often has multiple uses, and that it may also serve domestic needs or animal husbandry and other productive purposes. Whereas water can be stored in the unsaturated zone as soil moisture, or deeper down in aquifers, this paper is concerned with small and large surface reservoirs.

Any surface reservoir system whether large, medium or small-sized divides a catchment area into three distinct parts, and thereby also pushes its residents into three distinct roles (Figure 1):

(1) Upstream of the reservoir is the catchment area which generates the surface water that will flow into the dam. The owners or land users in this area will not (directly) benefit from the reservoir but their actions may be constrained by the needs of the reservoir. Since they provide a service to the reservoir they could be considered the "benefactors" of the reservoir.

(2) The centre is formed by the plots in the command area of the reservoir, which are intended to receive water from it, and whose owners are supposed to directly benefit. They are therefore the "direct recipients".

(3) Those located further downstream find themselves at the receiving end and feel the consequences of whatever has occurred upstream. They may thus be considered the "indirect recipients": they are not intended to directly benefit from the reservoir but may feel its impact due to a changed hydrological regime; this impact may be beneficial or harmful.

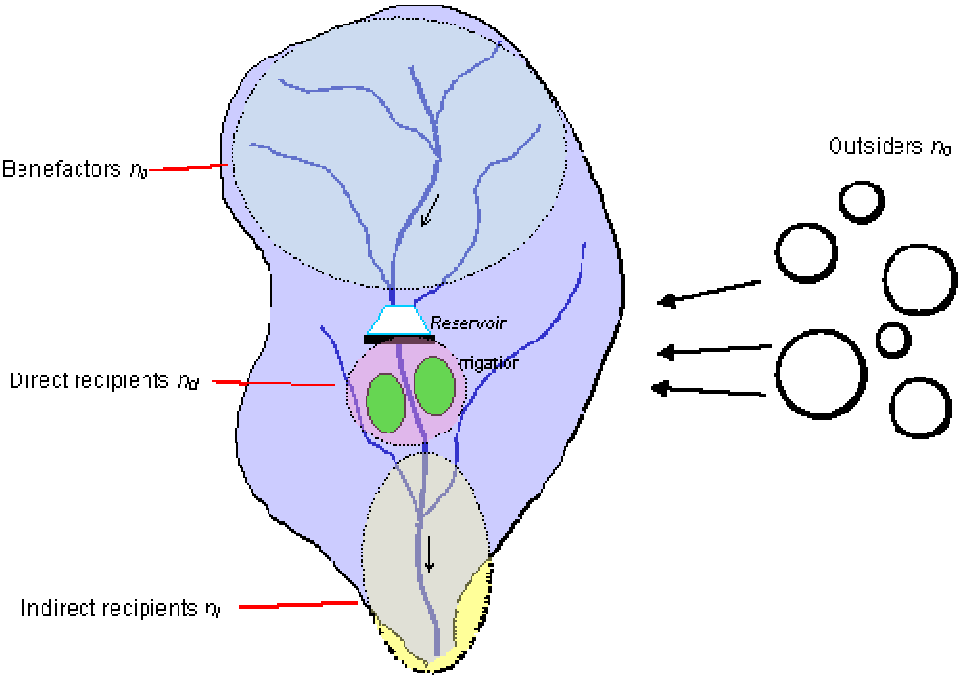

Figure 1: A reservoir divides a catchment area into three parts and its residents into distinct roles

In any decision on a new water storage project, there will be other stakeholders involved apart from the residents in the area. These include those who have the power and/ or interest in improving the water facilities in the area (e.g. those who invest; those who wish to purchase the products for further marketing; those who want to deal with poverty reduction strategies for the country etc.); and those who are afraid that there may be negative percussions for areas beyond (e.g. those who are afraid of the environmental consequences – since large reservoirs in seismic zones can be problematic, some reservoirs can lead to major emissions of greenhouse gasses and the general impacts of collecting water large scale in one reservoir or small-scale but in many small reservoirs on the hydrological and ecological system).

3. Some theoretical considerations on scale

In order to develop a common theoretical framework for assessing different water storage options, this paper takes the concept of scale as a central parameter. Since many different disciplines focus on different aspects of scale, scale provides a unifying platform for analysis. Scale is an analytical ruler against which one can measure (Gibson et al. 2002; IDGEC 1999/ 2005; Young, 2002). In environmental and water related issues relevant scales include the spatial scale, the time scale, the resource scale (Gupta and Van der Zaag, 2007) and the scale of governance (Gupta 2007b, forthcoming). Levels are points along each scale. Scaling up and down is the process of moving up and down levels within scales. Cross-scale interactions refer to movements or relationships between different scales. Cross-scale interactions would pose fewer challenges if scales were in general involving linear processes. However, since many of the processes involved in water and environmental management are non-linear, this means that upscaling and downscaling (increasing or decreasing the temporal and/or spatial scale) of interventions may have unanticipated results.

3.1 Scale issues in the natural sciences

Many hydrological processes are non-linear, an example being the sudden transition between laminar and turbulent flow of water. Many processes are determined by thresholds, such as the partitioning of rainfall into interception, surface runoff, infiltration and evaporation: rainfall below a certain value will only result in interception losses and will not generate surface runoff (Savenije, 2004). Increasing the intensity of rainfall radically changes the proportions in which the water is partitioned. Such non-linear processes exist in space and time. This means that observations made at a certain scale cannot automatically be deduced from observations made at other scales, and thus that extrapolating data sets is not unproblematic. For example, soil loss measured from a 10 m^2 trial plot may not be multiplied by a factor 1,000 to estimate the net soil loss from a 1 hectare field, or by a million for a 1,000 ha watershed. This is because at the (1,000) hectare scale some re-deposition of soil particles within field (watershed) may occur (Bagayoko, 2006). Swallow et al. (2001) call these areas of deposition “filters”. Similarly hydrological processes at the plant scale (1 m^2) are dominated by discontinuities within the topsoil, such as absence or presence of cracks and root systems of plants, which determine the magnitude of preferential water flow patterns. These discontinuities make it difficult to adequately model micro-scale processes. At a larger spatial scale, however, such processes are often much easier to estimate as some of the discontinuities may be averaged. At this scale other processes are dominant (Uhlenbrook, 2006).

With increasing scale the interactions between the various parts may give rise to new, emergent, phenomena. This is probably the major reason why up- and downscaling is problematic. One could argue that in trying to upscale or downscale biophysical processes, the systemic properties of those processes come to light. Sometimes the emergent phenomenon is that of self-similarity and self-organisation, whereby the processes occurring at smaller spatial or temporal scales are repeated at a larger scale. The shape and form of river channels and alluvial estuaries, for example, may not always be surprising (Savenije, 2003), as is the dendrical shape of some rivers that is repeated at various spatial scales. These may be considered fractals (Rodríguez-Iturbe and Rinaldo, 2002). Here the large temporal dimension (millennia) has shaped the spatial dimension (features of the landscapes) leading to a certain dynamic balance between various biophysical processes which give rise to certain coherent forms but not to a static equilibrium. This may have features of “self-organised criticality” that are found in many natural systems (cf. Ball, 2004: 295-300).

The above implies that a certain physical intervention in the landscape at a given scale that causes a small disturbance of certain biophysical processes, could cause a disproportionate (or negligible) disturbance at another. Similarly, such an intervention could yield large benefits if appropriately scaled and small at other scales.

In the context of this paper it is useful to identify appropriate indicators that are sensitive of such scaling issues in water storage projects. We argue that a useful indicator is the *residence time* $\boldsymbol{T_r}$ of a water particle in the reservoir, which is the quotient of the storage capacity and the average amount of water flowing into the reservoir. If the water flow is expressed as the mean annual runoff, then the residence time would have as its unit -- years. Many reservoirs have residence times in the range of 0.2 to 2 years.

Residence time is an intriguing indicator. It first of all expresses the claim a storage project makes into the future, as a kind of a temporal footprint. But interesting enough it also encapsulates the spatial dimension: it expresses in a temporal unit its spatial dependency and area of influence. The larger the residence time of a reservoir, the greater its dependence on the water resources generated in the upstream catchment area, and the larger the area downstream which senses its impact (cf. Vörösmarty et al., 1997).

Beyond a certain residence time a reservoir becomes the dominating factor in a river’s hydrology, and starts to create significant and measurable upstream-downstream interdependencies. The precise value of this critical residence time is not known but is likely to fall in the range of T_r = 0.5-1.5 years (Figure 2). The residence time of a reservoir is typically related to its function. If its function is to satisfy the requirements of a city’s water supply high levels of reliability (higher than 95%) are required and hence over-year storage is the norm (large storage capacity enables long-term buffering), which necessarily translates into large residence times. Full-scale irrigation would require large amounts of water supplied at levels of assurance level of at least 75%, whereas for supplementary irrigation storage is for short periods of time.

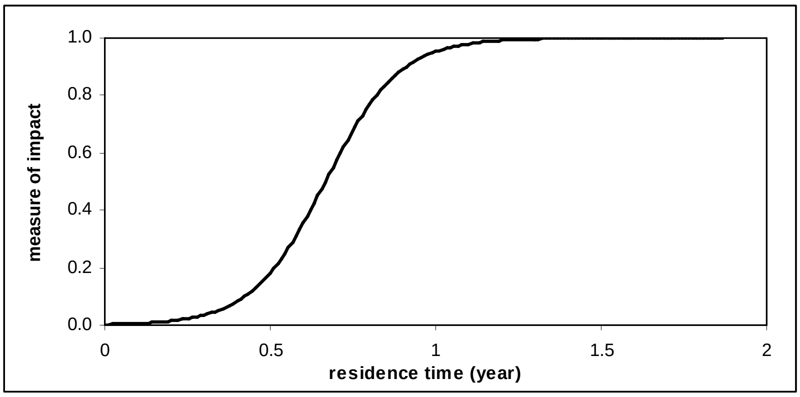

Figure 2: The relation between residence time and impact is non-linear

A second indicator, specific for agricultural water use, is the *water provision capacity* ***W*** expressed as the depth of water layer (m), which is the storage capacity S divided by the command area of the reservoir (irrigated farm area) A_f. A value in the range of 0.2 m would indicate that the reservoir may provide supplementary irrigation water only, or that it is used as a balancing weir or a night storage reservoir, whereas values of 1 m and beyond would be typical for conventional full scale irrigation during the dry season.

On the basis of the above discussion, we can derive the following criteria for assessing storage options:

a) Residence time T_r [average time a water particle resides in the reservoir]
b) Water provision capacity W [gross water layer that a reservoir can supply to its command area]

3.2 Scale issues in the social sciences

Within the social sciences different disciplines deal with scale differently. We first discuss the theory of scale as discussed in the social sciences and then move on to identify two indicators that we think is of particular relevance for this paper.

In the social sciences, there is a growing convergence that there is neither an optimal scale nor an optimal level at which environmental and water related issues can be managed. There are no “objective” criteria that can help determine what this optimal level is. There are however a range of criteria and arguments that can be used to scale up/ down a problem and solution (Gupta 2007a; Gupta forthcoming). Examples of reasoning given to scale up a problem include the need to take into account externalities (Van den Bergh, forthcoming), to make policies cost-effective, to promote the common good (Benson and Jordan, forthcoming), to gain control, or to bypass other government agencies (Compagnon, forthcoming; Spierenburg forthcoming). There are a number of reasons for scaling down; sometimes it is to understand local causes, patterns and interests and the desire to improve the resolution of the solution; or the need to both mobilise and empower local actors to address their own problems (Vermaat and Gilbert, forthcoming; Spierenburg, forthcoming; Bulkeley, forthcoming; Van den Bergh, forthcoming). There may also be other reasons for downscaling – sometimes to transfer responsibility, avoid liability for externalized effects, to protect local actors, to implement budget cuts of central governments and/or to bypass the nation state (Gupta, 2007a; Compagnon, forthcoming).

This implies that actors are often making conscious choices about which sets of reasoning they would like to use to argue whether a particular scale should be used or whether a particular level should be used. Thus, economists often tend to focus on the resource scale and argue in terms of economies of scale. This would imply in the area of water, a choice in favour of relatively large storage works. Policymakers may tend to focus on the administrative/ jurisdictional scale and focus on guiding principles such as subsidiarity and decentralisation which focus on empowering local actors to address their own problems. Subsidiarity is the policy principle adopted primarily within the European Union that focuses on transferring power and responsibility to the lowest policy level. Decentralised governance systems are often supposed to enhance legitimacy by including a larger number of stakeholders and their context relevant knowledge. Such systems are expected to have a higher compliance pull since a larger number of local actors are involved in the decision-making process. However, in practice this may not always be the case. Policies of decentralisation are often linked to neo-liberal reforms such as trade liberalization, deregulation and privatisation that started in the 1980s (Nuyten, 2004: 104). Such reforms imply a shifting role of government in development processes: from state-led development towards the strengthening of both civil society and the ‘invisible hand’ of the market. This type of discourse may obscure the highly political content of such reforms (Shore and Wright, 1997: 8). The danger is, that decentralised democratisation may lead to “decentralised despotism” (Mamdani, 1996), especially in countries where large power differences exist. In the context of water resources management there are at least two aspects that further complicate processes of decentralisation. The first is that the new watershed and catchment institutions that are being established in many countries often are too weak to withstand their “capture” by local elites (see Waalewijn et al., 2005). Moreover, these new institutions often compete with already established local government institutions at the District level and may debilitate them (Van der Zaag, 2005). The second problem is that the subsidiarity concept in water resources management, as with many other environmental and resource management issues tends to be a hollow promise. As more and more externalised causes and impacts are to be taken into account, this often leads to a concentration of decision making at higher levels of authority: since certain decisions (e.g. concerning the allocation of scarce water) cannot be left to local stakeholders alone.

Such decentralisation processes often shift responsibility to lower levels without shifting resources and capacity and is often not successful. At the same time, from a policy perspective, there are moves towards harmonisation of policy and integration with other policy areas and this leads to scaling up problems and solutions to higher levels. The key message that emerges is that in the social sciences, scaling is seen as a highly political activity; a tool used by different actors to promote their own interests.

Designing projects that promote water storage are likely to be influenced by actors, each motivated by their own interests. The final choice that emerges from decisions made by such actors, will also have influences on the actors themselves; it may empower some at the cost of others by changing ownership patterns and access rules.

Although, scaling is essentially a social construct, we try to identify two criteria that could help policymakers and decision makers deal with the problem of choice between small and large scale storage options. Although many parameters are important, we identify two as critical for a poor rain dependent agricultural country. These include the investment (and ownership) dimension as well as the governance (and legitimacy) criteria.

The choice of storage options has investment implications. Investment often determines ownership. Who owns the infrastructure directly influences use rights, access, maintenance and other related issues. Ownership ranges from private ownership (individual and company) to public ownership (community to state). As investments in reservoirs change, ownership may change accordingly depending on the actors engaged in reservoir creation and maintenance. Such decisions may affect access and access rules to stored water. The creation of storage capacity always requires investments, either in kind or financially. By making such investments hydraulic property is created (Coward, 1986). The *investment* may be expressed as the total monetary cost of a storage reservoir M_t, as well as the investment cost per beneficiary (direct recipient) $M_t/n_d = \boldsymbol{M_d}$. Those who invest claim ownership or have certain preferential claims to the stream of benefits created by the investment. Households have the capacity to make their own investments, as is proven by the many terraced fields and indigenous irrigation schemes and commercial farming enterprises seen in many rural landscapes. However there is a limit to their investment capacity. They may pool their resources through cooperatives and they may also be eligible for micro and small loans to be able to invest in such storage systems. The establishment of large hydraulic works often implies that local users get caught in a complex web of relations with outside players, be they government, financial institutions and private companies. The larger the hydraulic work, the larger the investment required and the more complex this web will become, including the entry of foreign players on the scene. The effect of increasing the investment scale of a storage project on local users’ access to stored water may be complex and is difficult to predict. It is, however, likely to result in limiting the decision-making capacity of local stakeholders, while the financial control of investors will be strengthened (Wittfogel, 1957).

Above certain investment values, however, lock-in may set in. Projects may become too complex, not only technologically but also administratively, such that their planning horizons, and useful life, are stretched far beyond the usual planning periods of 5 years corresponding sometimes to the periods of political parties in power. This would imply that where projects are very large, societies may tend to make decisions simply because the existence of such projects influences the perceived decision space, and the investments embodied in these projects are difficult to be ignored (Janssen and Scheffer, 2004; Pahl-Wostl, 2002).

As was indicated in section 2 above, storage projects may affect a variety of actors, including benefactors n_b as well as direct and indirect recipients n_d and n_i (Figure 1). As the size of a storage reservoir is enlarged more and more actors are involved and need to be consulted in project management. Some of these are beneficiaries (direct recipients n_d and some indirect recipients), but many may be negatively impacted (some of the benefactors whose degrees of freedom are constrained because of the storage project, and those indirect recipients who are impacted negatively by it), or may be involved since they are funding the projects. The problem is that the roles and interests of these actors may differ and the decision challenge is to reconcile the differing interests, who will benefit or be affected by the reservoir, and whether it is possible to allocate the stored water in a manner that is considered economically efficient, socially equitable and environmentally sound.

With increasing storage volume, more people are likely to be impacted, and the number of potential tradeoffs and conflicts increases. Elsewhere we have argued that institutional complexity is not linearly related to the spatial scale of water projects, and we have hypothesised that a doubling in physical scale of water projects may in fact lead to quadrupling of institutional complexity. Institutional complexity was assumed to be related to the maximum number of bilateral relationships (coalitions or conflicts) between the different stakeholder groups (Gupta and Van der Zaag, 2007). Therefore, the number of stakeholder groups with different interests in a given storage reservoir, the number of involved *actors **A***, is an important indicator for the institutional demands such a storage project poses. And this is of course directly related to issues of governance and political legitimacy.

In sum, this section has defined two more indicators for assessing storage options:

c) Investment M_d [monetary investment cost of a storage reservoir per beneficiary]
d) Actors $A=n_b+n_d+n_i+n_o$ [number of actors affected by a storage reservoir]

4. Centralised and distributed water storage

After having identified four indicators that together would be able to reveal scale issues in water storage projects, we now turn to the subject matter of this paper, namely a more detailed description of centralised and distributed water storage options. The special focus is on satisfying the water requirements of food production in semi-arid savannah areas.

One may generalise that in many semi-arid and sub-humid savannah zones rainfed agriculture needs a water storage capacity of around 200 mm (Van der Zaag, 2007a). (Note that this capacity can be utilised more than once during one growing season.) Part of this capacity is in the soil profile but many farmers have to make do with poor soils with low water holding capacities that can only effectively store around 100 mm. This means that additional storage capacity is required in the order of 100 mm. For a one acre plot (4,050 m^2) thus about 400 m^3 of additional storage would be required.

The key question is where and how to develop such additional storage capacity. Here we distinguish the distributed and the centralised options. In the *distributed* approach

(Van der Zaag, 2007a, 2007b; Moench and Stapleton, 2007; Liniger and Critchley, 2007) additional storage is de-centralised and distributed in the farmers' fields (e.g. storing rainwater in the soil of non-tilled or ripped fields or fields that are ploughed along the contour or on terraced fields, and "harvesting" runoff water by storing it in small farm tanks), and at the scale of the micro-watershed and village (micro-dams and aquifers).

Here we consider the option that each farm plot would have its own small storage tank (50-500 m^3) that would drought proof (part of) the rainfed crop, as well as other domestic and productive uses of water of the farm household. The tank would capture ("harvest") surface runoff from relatively small uncultivated catchment areas (0.5-2 hectares), including from roads and the farm compound. The water could be hauled from the tank simply with a bucket or using a small pump. The investment required is partially done in kind (labour, locally available construction materials by the farming household; other construction materials, tools by an NGO), and in cash (projects funded by governments, investors or donors). This option is currently pursued for example in South Africa (the "water for food movement" of Ma Thsepo and the "war on hunger" programme of the Department of Water Affairs and Forestry).

The management requirements of the distributed approach are fairly modest. A small tank would not require decision-making beyond the individual farm household. Given its size it is unlikely that people located downstream (or the downstream habitat) would be affected by it, or would claim a stake in the water and demand to be involved in how this stored water would be allocated. Within the farm household, however, decisions would have to be made on using the little stored water for domestic purposes, for farming, for livestock or for other productive purposes. Household members would organise labour to haul the water out of the tank, and distribute the proceeds of the productively used water in particular ways. The maintenance requirements mainly focus on desilting the tank and servicing the pumping device. The division of labour and the control over the proceeds are likely to empower some at the cost of others. In many cases, the choice for large reservoirs may have negative impacts on poor farmers and on women.

The other option is the *centralised* approach whereby a (small, medium or large) reservoir collects surface water and farmers downstream of the dam that are connected to the canal or pipe system have access to supplementary irrigation. This option conforms with the conventional irrigation development approach, whereby many different design possibilities exist (large-scale, small-scale, farmer-managed, agency-managed, and combined systems). Most existing irrigation developments, however, are designed for irrigating a dry-season crop, which have a much larger irrigation requirement (in the order of 600-1,000 mm/a). As a consequence, relatively large reservoirs are required, and hence also a much larger catchment area from which water is captured compared with the distributed alternative. Irrigation schemes differ in size from 5 to 5,000 ha and beyond, the smallest requiring a reservoir with a minimum capacity in the order of 20,000-100,000 m^3, and a catchment area from which water is captured of some 20-100 hectares, depending on the precipitation patterns in a region. The largest reservoirs may have a capacity of $50\text{-}100 \times 10^6$ m^3, or more, and would be located on relatively larger rivers. Investments are typically done by development (domestic, regional or international) banks in conjunction with contributions by the government as well as by the beneficiary households. However, the latter may be very small.

The management requirements of the centralised options are significantly more complex compared with the distributed approach. First, reservoirs are normally equipped with gates or other devices that can be opened and closed. Since the stored water is supposed to benefit more than one farm household, some implicit or explicit arrangements regulate who decides when the gate is opened and closed, and how the water will be allocated over the plots in the command area. Also, maintenance has to be arranged, such as canal repairs, de-silting of canals and reservoirs, fencing etc. Given the size of the reservoir and its hydrological impact it is possible that downstream actors, including those concerned with the environment, would put forward certain demands on how the reservoir should be operated. The magnitude of the investment requirements for large reservoirs are likely to be significant, and these tend to have large power effects (Bolding and Van der Zaag, 2005), and may have differential impacts on the two sexes.

Table 2 provides typical values of design parameters of three different storage options: tanks, small reservoirs and large reservoirs.

Table 2: Typical design parameters and values of tanks and small and larger reservoir systems (cf. Keller et al., 2000; table 3)

Aspect	Unit	Distributed tank system [a]	Centralised reservoir system small [b]	Centralised reservoir system large
Catchment area A_c	1,000 m^2	20	1,000	150,000
Runoff Q	1,000 m^3/yr	3	150	25,000
Reservoir storage capacity S	1,000 m^3	0.5	50	50,000
Surface area of reservoir A_s	1,000 m^2	0.2	50	1,000
Net evap. and percolation losses L	1,000 m^3/yr	0	25	2,000
Residence time $T_R = S/Q$	yr	0.2	0.3	2
Presence of sluice gate/valve G	yes/no	no	yes	yes
Number of direct recipients n_d	household	1	20	2,000
Number of benefactors n_b	household	0	30	8,000
Number of indirect recipients n_i	household	0	10	6,000
Number of actors with power to influence the decision – investors, NGOs, government agencies	organisation	0	3	30
Storage capacity per beneficiary S_d	1,000 m^3/hh	0.5	2.5	25
Farm area A_f	1,000 m^2	5	100	20,000
Water provision capacity $W = S/A_f$	m	0.1	0.5	2.5
Travel time reservoir to plot T_p	day	0.1	0.5	5
Estimate of total investment cost M_t	1,000 US$	2	20	10,000
Unit investment cost	US$/m^3	4	0.4	0.2
Investment per beneficiary $M_d=M/n_d$	1,000 US$/hh	2	1	5

a) Typical values are derived from tanks being constructed in South Africa in connection with the “water for food movement” of Ma Thsepo.

b) Typical values are derived from and consistent with the many small reservoirs found in the Upper East Region (White Volta) in Ghana (Ofosu, 2007) and in Matabeleland South Province (Mzingwane catchment) in Zimbabwe (Sawunyama et al., 2006; see also Chimowa and Nugent, 1993).

The managerial complexity differs between these three systems, as is indicated by the size and number of farms *n* that each services: from 1 to 20 to 2,000 farms. The downstream impact also differs significantly: whereas the tank captures 20% of the surface water generated from a small 2 ha catchment area (T_r=0.2 years), and the small reservoir captures 30% of a catchment area of 100 ha (T_r=0.3 years), the large reservoir captures all the surface water generated in a 15,000 ha catchment (T_r=2 years). In the latter catchment area there seems to be little place for small tanks, since all the surface water is required to fill the large reservoir; it lays a strong claim on the water resources generated in the upstream catchment.

Because of the shorter residence times of the small reservoirs and tanks, their claims on the upstream catchment and downstream impacts are modest. Since rural landscapes normally consist of cultivated areas interspersed with non-cultivated areas, there will always be space for relatively small runoff harvesting structures such as tanks and small reservoirs.

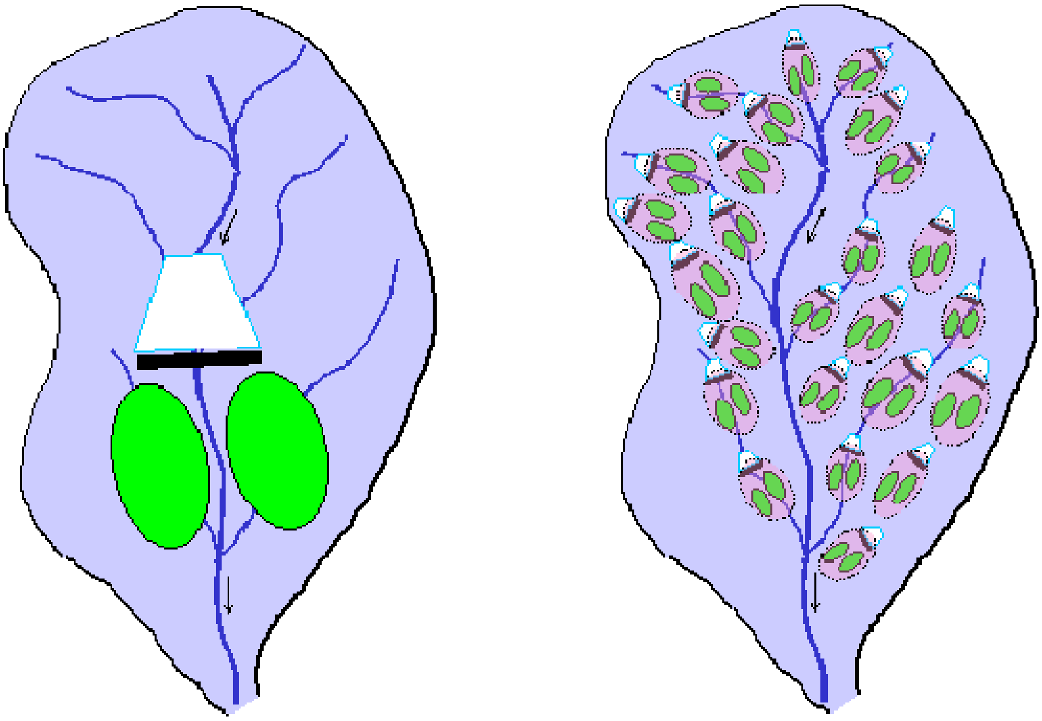

Figure 3: Different policy options: a centralised and a decentralised approach

An important difference between the various storage options is the water provision capacity expressed in meter water layer?, and indicates whether water is used for supplementing rainfed crops or whether it is used for irrigating a crop during the dry season. The former will increase water consumption by 100-200 mm per crop, whereas the latter by 600-1,000 mm per crop. This is a significant difference and reflected in the different water provision capacities *W* (0.1-2.5 m). In addition it should be noted that supplementary irrigation water has a much larger productivity than irrigation water for a fully irrigated crop (2 kg of grain per m^3 versus 0.5 kg of grain per m^3, Pazvakawambwa and Van der Zaag, 2000). In water scarce landscapes it may therefore be prudent to invest in supplementary irrigation for rainfed agriculture during the wet season combined with very small scale market gardening during the dry season, rather than in full-scale irrigation (dry and wet season).

The ownership of the various storage works is another relevant indicator and is related to the investment requirement per beneficiary household (M_d). Tanks, located as they are within a farmers' plot or compound, are likely to be perceived as fully owned by that household, even if the investment is significant (about M_d = 2,000 US$/hh) and the construction was subsidised. A small reservoir is normally located near a village and is often identified with it. Rules of access and exclusion may pose some problems since not all villagers may benefit from the reservoir in similar ways. However, a system of local scrutiny and accountability will still be possible. Also local ownership is consistent with relatively low investment costs (about M_d = 1,000 US$/hh). The large reservoirs are large in many ways, including their investment requirements (about M_d = 5,000 US$/hh). It is therefore likely they will be controlled by central government agencies, which may ignore local governance practices.

Turning to the arguably major governance indicator, that of the total number of actors somehow involved in a storage scheme, we contrast the tank, in which one household is not only the direct beneficiary but also provides the catchment area, whilst the indirect impacts of the tank are beyond detection level (A_{tank}=1), with a small reservoir that has 20 direct recipients and that depends on a catchment area occupied by farms of in total 50 households, of which 20 belong to the group of direct recipients. In addition, the downstream impact may be felt in total by 10 actors ($A_{small\ reservoir}$=60). Finally, for the large reservoir typical numbers are 2,000 direct recipients, a catchment area occupied by 8,000 farms or households, and the impact downstream is assumed to be felt by 6,000 actors ($A_{large\ reservoir}$=16,000). It should be noted that these numbers are indicative only and will differ from case to case. If expressed per direct beneficiary (A/n_d) these numbers reflect the normalised externality of each storage option: 1, 3 and 8. Whereas a tank only affects the farming household itself, a small reservoir influences two other households, while a large reservoir may impact 7 households per direct recipient household.

A final non-linear phenomenon concerning reservoirs should be noted. The small tanks and reservoirs meant for supplementary irrigation have low residence times, meaning they may fill several times per season and hence silt up relatively fast. This puts a strain on maintenance needs. The extreme case is sand dams which are purposely built to silt up and store water underground, so that evaporation losses are reduced.

5. Discussion

We have identified four relatively straightforward indicators to identify scaling effects in storage projects. These are residence time T_r, water provision capacity W, the investment cost per direct recipient M_d, and the total number of actors A involved and affected by a storage reservoir. Interestingly, these indicators contain and combine hydrological, engineering, agronomic, and the social sciences. They define and link different scales, each of which has certain degrees of non-linearity, and as these non-linearities are not necessarily symmetric, their combined effects in terms of management requirements and governance may be difficult to predict. Table 3 summarises the major non-linear processes that these four indicators refer to, as well as some of the implications these may have.

Table 3: Indicators and non-linearities

Scale	Indicator	Explanation	Non-linearities	Implications
Temporal-spatial	Residence time $\boldsymbol{T_r}$	Average time for a reservoir to fill [year]	Beyond a certain residence time a reservoir becomes the dominating factor within its area of influence, and may have higher environmental impacts	*Legal-administrative:* with larger impacts licensing procedures become important and environment impact assessments have to be carried out
Capacity	Water provision capacity $\boldsymbol{W}$	Capacity to fulfil specific water need [m water layer]	If the water provision capacity shifts from supplementing rainfed agriculture to full dry season irrigation, downstream impacts on the flow regime will increase significantly	*Socio-economic*: with increased access to water, households, communities and societies may lift themselves out of the poverty trap. *Environmental:* impacts change with project size; often harmless or even beneficial when small but harmful as size increases
Ownership	Investment per direct recipient $\boldsymbol{M_d}$	The degree of resources invested	Small investments may not lead to change; larger investments may be more cost-effective; still larger investments may lead to lock-in. As investments increase more extra-local actors get involved which may lead to change in ownership. This has implications for access and rules of access to the water, as well as maintenance.	*Political:* increased investments and values tend to be accompanied by heightened political interest and interference *Legal:* as increased costs lead to public-private partnerships that involve non-nationals international commercial and investment law rules become applicable.
Governance	Number of households involved and affected and number of outside actors influencing decision-making $\boldsymbol{A=n_b+n_d+n_i+n_o}$	The number of actors involved in decision making	As projects increase in size, more competing claims and interests get involved, which need to be reconciled. This puts an increasing burden on institutional capacity for legitimate decision-making processes.	*Legal-administrative:* as projects increase in size, they cross jurisdictions, making the administrative processes more cumbersome

Increased provision of storage capacity may increase a household's access to water, and may help to lift households, communities and societies out of the poverty trap. The larger the size of a water reservoir, the larger its geographical area of influence, the more persons will be affected by it, either in positive or negative ways, and the more difficult it may be to reconcile the competing claims and interests of those involved. Larger reservoirs thus require increasing institutional capacity to design and implement decision-making processes that are perceived as fair and legitimate, and that lead to outcomes that will be acceptable and enforceable. Environmental impacts change with project size. Small dams may have fewer environmentally harmful impacts or may even have positive environmental externalities, but the larger the size of a project and the larger its imprint on the landscape (through an increased residence time), the more harmful it may become; including earthquake risks where these are constructed in seismic zones (Gaur 1993). Also the administrative burden may increase with size, especially when larger impacts will require certain licensing procedures, and as these impacts cross jurisdictions new administrative complexities are added. Finally, if a reservoir requires investments that go beyond the capacity of the direct recipients, these beneficiaries may get involved into new relations with outside financiers, which may not always turn out to be an empowering experience.

This analysis tends towards the "small is beautiful" and is perhaps a reaction to the era of large dams and the outcry against them (e.g. Morse and Berger 1992). However, small interventions are not enough to insure societies in semi-arid ecosystems against the vagaries of the climate. The small interventions need to be replicated on a large scale. It is illustrative that Zimbabwe around 1993 had as many as 10,000 dams (of which 8,000 small reservoirs; Chimowa and Nugent, 1993), and was one of the Sub-Saharan countries best endowed with water storage capacity,[1] yet this was not sufficient to drought-proof its economy: the stock exchange and rainfall levels were known to be strongly correlated.

So even if the option of small reservoirs would be chosen, a massive and large-scale intervention is required, which may have large ramifications. The cumulative effect of very many cascading tanks and small reservoirs spread across the landscapes, in terms of hydrology, ecology and governance should be an urgent field of research. To exaggerate the point a bit: by now we have a fairly good idea of what the biophysical, economic, managerial and socio-political impacts are of large dams (WCD, 2000). But do we know the precise impact, the economic, social and ecological benefits and costs as well as the socio-political effects, of one million small tanks with a capacity of two hundred cubic meters each, and how this compares to the impact of one large reservoir with a size of two hundred million cubic metres?

One could argue that the distributed approach of upscaling storage would result in a better spread of access to storage space, and is less easily monopolised as in the case of large reservoirs. In terms of water allocation at the basin scale, however, the distributed approach may pose nightmarish challenges: would it still be possible (physically and

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[1] Zimbabwe had around 650 m^3 per capita storage capacity (Chimowa and Nugent, 1993), noting that access to this storage was unevenly spread, with the 4,500 large scale commercial farms having 77% of all dams. South Africa has 687 m^3 per capita, quoted by Grey and Sadoff (2006) as being the highest of Sub-Saharan Africa.

administratively) to release stored water in upstream catchments to satisfy legitimate needs in downstream parts of the basin? The answer hinges on the precise hydrological impact of such an approach, which depends on the average residence time of each of these small structures, which part of the hydrograph is captured by it, and whether a significant part of the command area will be fully irrigated during the dry season or not. In terms of the larger governance issues, one could ask whether the distributed approach would indeed foster and be consistent with the decentralisation of water management, or whether it may trigger the need for a centralisation of decision-making. Would the distributed approach lead to equitable development or, again, to hydraulic despotism?

6. Conclusion

As climate change becomes a greater threat to countries in terms of impacts on water systems, all countries, and especially those with semi-arid climates, need to think more about how best to manage and store their water resources. Adaptation to global change requires not only changes in the ways we manage water, but also requires new judicious physical interventions, in particular in creating more storage capacity. Such physical interventions are inevitably accompanied by large investments, which have implications for ownership and access to water, and thus may influence power relations in the local economy. A reservoir, whether large or small, divides a catchment area in three parts, and pushes its residents in distinct roles. The central issue discussed in this paper is that the sizing of storage infrastructure is not straightforward because of a variety of non-linear implications, including on governance.

To enhance the capacity of livelihoods to cope with climate variability, their access to water storage should increase significantly. The policy choice is what form the additional storage should take: should the centralised option be preferred with relatively few large reservoirs, or the distributed option with many small reservoirs and tanks, or judicious combinations thereof.

The distributed approach has many advantages, in terms of ownership, management and environmental aspects, yet expressed per unit storage it is much more expensive in monetary terms than the centralised option (the latter may exclude more tangible and intangible externalities than the former).

Whatever option is chosen, storage is seen as an asset; and should as such feature in the annual accounts of all semi-arid countries. The average cost of creating 1 m^3 of storage ranges between 0.2 and 4 US$/$m^3$ (see Table 2). If as a minimum 700 m^3/capita is required, emulating South Africa, this would translate into an investment requirement of 140 to 2,800 US$/cap; figures that are in the same order of magnitude as one year GDP of the countries concerned. So is it realistic to assume that such massive investments may ever happen?

A number of indicators were identified that encapsulate interesting and cross-disciplinary information, including the residence time and the investment per beneficiary. In so doing the paper has contributed a number of ideas about how choices between scalar interventions can be made in a context relevant manner.

This paper did not take cost-effectiveness and the economies of scale as an individual indicator since these indicators capture only one idea – the notion of cost. Such simplistic ideas often motivate decision-makers to go for the cheapest option: large reservoirs. This paper has indicated that there are complexities associated with large reservoirs that may be difficult to overcome and require strong institutional capacity if unwanted consequences, such as unequal access and environmental impacts, are to be mitigated. One would thus have to judge whether this institutional capacity is such a scarce resource and so difficult to build up that for the time being priority should be directed to those storage projects that minimise institutional complexity. This would favour the distributed approach that would create very many small, but per unit storage more expensive, tanks and small reservoirs.

Such tanks and small reservoirs will increase the insurance of livelihoods against dry spells. These would significantly increase the water value through slowing the water flow in the landscape, while having a limited negative impact on upstream and downstream areas. In addition, the managerial requirements of operating those storage devices would be limited compared to larger reservoirs. In terms of managing the entire catchment in which these devices would be located, the precise governance requirements are unknown, but could possibly be limited as well, simply because only a relatively small portion of the generated runoff would be captured and withdrawn. A positive externality of the small reservoirs would be seepage losses that would recharge aquifers on which those and neighbouring farmers would rely and benefit from. Having sources of water scattered across the landscape may also have other benefits: more water will be available for other, high-value productive uses.

Once water availability is significantly enhanced and secured, farmers will be more confident in harvesting a good crop, and thus can afford to invest in chemical fertilizers. The combined effect of improved water and nutrient management can be spectacular and is likely to lead to doubling or even tripling of crop yields (Rockström et al., 2003; Falkenmark and Rockström, 2004; Falkenmark and Lannerstad, 2005).

Empirical analysis in a number of different fields shows that it is not always the size of the project that guarantees its success, but the way it is embedded and integrated in the local community that often ensures that such a project is successful. For example, in the area of rural electricity, even small scale rural electricity schemes may be successful if they are well integrated into a larger rural development plan that stimulates not just consumptive use but also productive use of the electricity leading to the generation of resources to make the whole scheme viable (Rangathanathan, 1993). Swallow et al. (2006) emphasize that the various spatial scales are linked and nested as fractals: that success at one scale increases the return to investment at other scales; but also vice versa. They therefore make a case of the need for concerted efforts at various spatial scales simultaneously. It is also of vital importance that the project is design in a manner that it is compatible with the enabling environment (Hahn, forthcoming) and that it is consistent with historical and customary practices as this is more likely to be successful.

If the challenge of integrated water resources management is the reconciliation of social equity with economic development and environmental integrity, one could argue using Toulmin's methodology that:

- when water storage capacity is low, it will be difficult to achieve economic development and social equity, since water access is assumed to be critical for agricultural productivity, unless societies move towards restructuring towards being less agrarian and more industrial.
- when water storage capacity is increased economic development is more likely, yet social equity is not automatic and contingent on the technology and associated social rules (centralised large or distributed small); environmental and other impacts are starting to being felt; since increased capacity may be accompanied by changes in ownership patterns which may limit water access to those without economic or bargaining power; unless such provisions are expressly included in national legislation and in the contracts with the private parties. For example, South Africa has special legislation that calls for including women in management positions in projects of a certain size.
- when water storage capacity is maximised, economic development may not be necessarily maximised as environmental impacts have economic drawbacks; since a general rule of thumb is that the larger a project, the larger its negative externalities and these externalities may have impacts on a society, unless a quality social and environmental impact assessment was carried out prior to the project and the project was approved.

Increased access to water storage will, if properly combined with investments in other fields, such as road infrastructure, markets, knowledge and information, trigger economic growth. Such a development may in turn require a further increase in buffering capacity, and thus the creation of more hydraulic property. With such investments the dangers of inequity loom large. The institutional capacity of governments to mitigate these effects and to provide for public good functions, and to defend the public interests must therefore be considered key. But ironically institutional capacity may as much be a result of this development as a prerequisite.

Finally, it is urgently required to conduct research into the cumulative effect of the distributed option, whereby many cascading tanks and small reservoirs are littered across watersheds, both in terms of hydrology and governance.

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