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Equilibrium and non-equilibrium theories of sustainable water resources management: Dynamic river basin and irrigation behaviour in Tanzania

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Abstract

The model of a variable climate driving natural resource behaviour, use and management of rangelands in Sub-Saharan Africa has been well explored within the non-equilibrium ecology discourse. This paper argues that concepts found in rangelands non-equilibrium thinking have considerable utility if applied to irrigation and river basin management in African savannah landscapes when irrigation has grown in area and coalesced into a larger behavioural unit. The paper suggests that a theory of transition is common to successful rangelands and water management under non-equilibrium conditions. A framework of sustainable water resources utilisation underpinned by non-equilibrium thinking is presented, and some conceptual concerns regarding normative management solutions to water scarcity in Africa are illuminated. Alternative solutions are underpinned by managing water within, and facilitating transitions between, three water supply states: critical water; medial water and bulk water. The discussion is informed by a case study from southwest Tanzania.

Keywords: Non-equilibrium; Ecology; Irrigation; River basin management; Tanzania; Variability; Water resources; Sustainability; Natural resources; Adaptive capacity

1. Introduction

This paper examines how concepts of non-equilibrium rangelands in Sub-Saharan Africa have parallels with, and critically inform, the sustainability and management of irrigation and river basins. While climate variability is noted as a key feature of semi-arid landscapes in Africa, and a considerable literature has grown around rangeland management and pastoral livelihoods (Behnke et al., 1993; Leach and Mearns, 1996; Walker and Abel, 2002), less attention has been paid to how irrigation systems and livelihood practices adjust to climatic variation as part of a dynamic ecosystem. Climatic fluctuation is used as a rationale for tackling problems of food security and poverty: "Among factors that contribute to risk in Tanzania's agriculture is the unpredictability of rainfall and the recurrence of drought and floods. Soil and water management practises must be improved in order to reduce these risks and improve the productivity and profitability of agriculture" (MAFS, 2001, p. 35). However, what it means to plan for and manage *uncertainty* and *considerable variability* of water supply in irrigation and river basin systems is poorly explored beyond the provision of irrigation or storage infrastructure, which is conventionally held up as a solution to water shortages in such environments. Variability of water supply is addressed by Adams' overview on irrigation interventions in sub-Saharan Africa, suggesting it is a primary cause of failure of large-scale irrigation schemes. However, he does not discuss how irrigation managers might cope with or adapt to water variability; rather, he suggests "less optimistic forecasts of project performance … are likely to be both more achievable and more sustainable" (Adams, 1992, p. 89).

We contend that to generate satisfactory irrigation performance at the river basin scale, responses to a dynamic climate have to move beyond the size, institutions and physical design of irrigation provisions to address cross-scalar water use (local to basin scale) and

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cross-state[1] levels of water supply (scarce to abundant). In other words, addressing water variability requires a basin-wide and resource-centred approach rather than an irrigation-focussed approach based on stabilising and securing flows (Lankford, 2004a). Otherwise, straightforward irrigation solutions, often unadulterated within an integrated approach, capture, magnify and export contextual variability for water users within and downstream of irrigation systems. In addition, we contend that only by examining water for irrigation in the context of wider agro-ecological systems and local-to-basin institutional frames can the capacity to cope with uncertainty and variability of water be constructed.

This paper, based on research in the Usangu Basin in Tanzania over the last 7 years, has a particular emphasis on irrigation systems as the primary demand for water in many river basins in Africa, and as an increasing focus for productive livelihoods and consequently donor and government interest. A dynamic irrigation system can be characterised ''by its ability to dramatically change the area supplied, planting schedules, number of farmers supplied, run-off volumes and efficiency'' (Lankford and Franks, 2000, p. 6). We explore how this fluctuation takes place within the boundaries of existing irrigation technology and land ownership and what wider agro-ecological dynamics exist. The role fluctuation plays in livelihood strategies, how cultural and formal institutions react to change in water availability and the implications for the sustainable management of water are also examined. We draw on non-equilibrium ecology to argue that sustainable water management is defined as facilitating water-based productive, healthy livelihoods and ecologies by the managed transition of the river basin between three different water states or phases related to rainfall variability: 'critical water', 'medial/scarce water' and 'bulk water'. This is supported by building resilience and flexibility via innovative legislative frameworks and technology, conflict resolution and by examination of the factors affecting the distribution of small amounts of water required for domestic users, wildlife and livestock. Our state-transition approach is wholly different from the 'non-equilibrium' paper of Geldof (1995) that addresses flexibility, but via an eclectic mix of 'perpetual novelty', moving from 'the global to the local', communication and incorporating history.

To introduce our analysis and distinguish it from earlier debates, we explore two key literatures that have dominated the discussion of how water-based livelihoods and ecology in semi-arid regions have been constructed; 'wetlands in drylands' and 'small-scale irrigation'. The 'wetlands in drylands' literature explores, in scalar terms, small areas where water accumulates in depressions, wetlands and dambos in otherwise arid areas (Scoones, 1991; Woodhouse et al., 2000). These wetlands represent one kind of 'patch' within the patches that make up savannah systems in Africa, exploring the livelihoods, local conflicts and management strategies associated with these 'oases'. The discourse, which stresses the importance of wetland production in predominantly rainfed agricultural systems, does not fully explore conceptual parallels between the two, particularly at the larger scale, or apply these parallels to the analysis of appropriate management of river basins. For example, cross-scalar tensions regarding how very large evaporative areas deplete downstream users are not developed because these wetlands singularly or in combination tend not to be great enough in areal terms to substantially affect the behaviour of each other or of other sectors in the river basin.

During the last 20 years, in a second literature, scientists discussed small- and large-scale irrigation, where irrigation size was used as a proxy for complexity and behaviour. Underhill (1990) suggested four classes of irrigation scheme, indicating a link between size, complexity, management and need for water control: very large schemes over 10,000 hectares (ha) with full water control; large-scale schemes, 1000 to 10,000 ha, with full water control; medium schemes, 100 to 1000 ha, with full or partial water control; and small schemes, 1 to 100 ha, controlled by farmers, groups or single farmers. Small-scale irrigation was associated with the rangeland discourse because irrigation sustainability and rehabilitation projects were critiqued on the basis of scale. Thus, just as institutionally allying the rangelands with the non-equilibrium pastoralists was deemed 'sustainable', managing the water commons by smallholders was considered more appropriate because they were seen to be more efficient. Evidence pointed to the generalisation that smallholders 'did it better' (Adams, 1990; Underhill, 1990; Venema et al., 1997), while large-scale projects were criticised for being inefficient (McCully, 2001; Moris, 1991), facilitating unequal land tenure development (Carney, 1993) and enshrining unequal access to water resources by position in the canal system, gender or political class (Woodhouse et al., 2000; Woodhouse, 2002; Adams, 1992).

Although more critical viewpoints existed (Carter, 1992), examining river basin and water systems behaviour on the basis of the size of individual irrigation systems is limited for four reasons. Firstly, size partially recognises a system's functioning and behaviour. Irrigation systems may be the same size, yet have different socio-technical workings. Secondly, 'small-scale irrigation' discourses are in danger of idealising community-level management as consensual, flexible and less bureaucratic, whereas community management of water resources is often highly conflictual, based on political negotiation and social hierarchies (Mosse, 2004; Woodhouse, 2002). Thirdly, scale descriptors fail to capture the dynamics of irrigation that stem from areal growth, water competition and climate variability. Widespread growth of small-scale irrigation in many African river basins leads to emerging interconnectedness and large-system behaviour. This happens when cropping areas

[1] States are explained in the paper. They are categories of different water supply amounts—critical, medial/scarce and bulk are states used in this paper. Definition of medial: median, middle.

of small-scale irrigators accrue in geographic proximity (seen in Usangu or in Senegal described by Venema) or who are distant from each other. This is because in a river basin, or aquifer, the 'common propertyness' of irrigation is dictated by water loss by evaporation and not by geographical distance. It is not the size of an individual canal network that dictates complexity and behaviour but the coalesced area of evapotranspiration in relationship to the metrics of supply. Related to this is a fourth point; when demand exceeds a river's supply along its reach, the river switches in behaviour—it no longer supplies surplus water to autonomous points of demand but becomes a contested channel with infrastructure that divides and defines the distribution of a scarce resource. These division points, with associated legislative and institutional frameworks, become battlegrounds over water (Pradhan and Pradhan, 2000). Taking these points together, the imperative is to understand the behaviour associated with 'coalesced irrigation' in variable, water-short environments—and it is these characteristics at the basin scale that are pertinent when exploring parallels with non-equilibrium rangelands.

1.1. Case study

Situated on the escarpment the rift valley, the Usangu Basin covers 21,500 km^2 at the head of the Great Ruaha River. In the basin, six water sub-systems can be identified. First, run-off is generated from the Kipengere highlands to the south, and the Chunya escarpment to the west. Second and third, run-off feeds irrigation systems and alluvial plains. Fourth, rivers supply seasonally flooded grasslands and in the centre of the catchment, a perennial swamp. Fifth, these wetlands feed the Great Ruaha River, which passes through the Usangu game reserve and the Ruaha National Park, before supplying two large-scale hydroelectric projects (Mtera/Kidatu) that are central to economic prosperity in Tanzania. The catchment is marked by competition for scarce water among these users and over a large scale, between upstream and downstream users. Analysis indicates that total potential consumptive needs far exceed supply except in the wettest of years, and that irrigation in particular is the major user of water, and growing fastest, and as such has been the focus of many interventions and research projects examining water management. For further details and illustrations, see Baur et al. (2000); Franks et al., 2004; Palmer-Jones and Lankford (2005).

2. Equilibrium and non-equilibrium theories of water resources management

A conceptual framework of the parallels between rangelands and irrigation/river basins is proposed in Table 1, which is divided into two columns, 'equilibrium' and 'non-equilibrium', each being divided again; 'rangelands ecology' and 'irrigation and river basins'. In the top, four rows summarise the resource behaviour, livelihood responses, sustainability concepts and implications for resource management. In the lower half, the table dispenses with these parallels to concentrate on some key issues in the management of river basins informed by equilibrium and non-equilibrium thinking. With limited space, the points in Table 1 are not repeated in the main text; rather Table 1 is employed as a guide to the paper's structure and general objectives.

2.1. Summary of resource behaviour and response

Rainfall and water variability underwrites the ecological dynamics of African savannahs. Models of non-equilibrium ecology suggest that semi-arid grasslands are driven not by a continuous accumulation of biomass but by episodic events governed by abiotic factors, predominantly 'pulses' of water or fire. Savannah ecosystems, such as the Usangu plains, may never reach a state of equilibrium, but exist in a state of flux between wetter and dryer conditions. The instability of seasonal rainfall means the ecosystem does not move towards a resilient, stable 'climax' ecological community, and transitional states should be seen as part of a wider ecosystem dynamic (Sullivan, 1996, 2003; Suding et al., 2004; Holling and Gunderson, 2002; Marchand, 2002; Walker and Abel, 2002; Behnke and Scoones, 1993). This understanding has led to the re-evaluation of nomadic livelihoods that appear to maintain higher concentrations of cattle across a landscape than suggested by conventional calculations of carrying capacity, a concept based on non-variable equilibrium models of rangelands. The discourse addresses how the foundations of two different ecologies (equilibrium and non-equilibrium) underpin different models of sustainability and management (enclosed and open range management).

To explore how non-equilibrium applies to irrigation, we first outline the climate of our case study. Seasonal variability in Usangu is marked (from zero rainfall during the dry season to approximately 150–200 mm/month in the wet season), driven by north–south movements of the inter-tropical convergence zone, causing a bi-modal pattern of rainfall over equatorial east Africa (Ellis and Galvin, 1994). Inter-annual variability in east Africa is related to the El Niño Southern Oscillation, which moves Indian Ocean weather cells over the land, causing high-pressure stable dry conditions, and La Niña events that bring wet conditions (McGregor and Nieuwolt, 1998; Adams, 1992). Although the central Usangu plains receive between 600 and 800 mm average annual rainfall, in a dry year, wet season rainfall may be less than 300 mm, while in a wet year, wet season rainfall can exceed 800 mm (Machibya, 2003; Fig. 1). Similarly, a study of the Rufiji Basin by the FAO in 1961 noted that annual discharges from the Usangu plains "varied almost 100% between low and high years" (SMUWC, 2001, annex 1, p. 12). The mean coefficients of variation of rainfall for different sub-catchments in Usangu lie between 25%

Table 1
Framework for comparing equilibrium and non-equilibrium rangelands and irrigation and river basins

	Equilibrium		Non-equilibrium	
	Rangelands ecology	Irrigation and river basins	Rangelands ecology	Irrigation and river basins
Summary of resource behaviour and response	Ecology moves towards a climax sequence of vegetation, predictable resource growth and offtake.	Irrigation developed and fitted to predictable availabilities of water supply. Demand for water and command area (CA) is closely ascribed, independently determined, more constant and is assured water.	In semi-arid environments, pulses of rain and fire, and higher evaporative demand, affect ecological sequencing.	Irrigation develops ad hoc, responds to availabilities of water. Demand matches supply. CAs and boundaries dramatically change, but maximum CA is not assured supply over time, subject to rainfall variability.
Livelihood system response (and counter-narrative)	Fixed pasture grazing at stable carrying capacity (nomadic land management leads to over-grazing).	Irrigation infrastructure will stabilise and maximise water supply (efficient water use undermined by opportunist/illegal irrigation).	Pastoralists maximise herd size and are mobile/flexible. (Flexibility of response now being undermined by changing land tenure and competition.)	Farmers expand area in wet years and contract in dry years. (Individual farm areas and livelihoods differentially respond to water variability as mediated by many factors.)
Concepts of resource sustainability	*Not discussed in this paper.* Growth and re-seeding rates determined so that 'take-off' rates and timing do not undermine ability to self-generate. Concepts of thresholds that should not be transgressed apply.	*Not discussed in this paper.* Monsoonal or temperate climate coupled with groundwater resources implies that irrigation demand is matched to predictable, sustainable yield of environment. The threshold of demand should not exceed supply.	Supply and thresholds are dynamic, boundary conditions incorporated. Resilience is promoted by allowing movement across landscape, a form of facilitated transition between different conditions of resource availability.	Exogenous supply coupled with low aquifer storage results in decoupling of one year to another: sustainability and thresholds of supply and demand are quantitatively difficult to ascribe and fix. Sustainability is addressed via facilitating transitions between, and sharing of waters within, three key phases: critical water; medial water and bulk water.
Institutional approach to sustainable management	Rangelands carrying capacity determined, stocking fences, rates, cycling. Cattle-keepers encouraged to adopt settled patterns of land tenure.	Small-scale infrastructure provided and 'improved' by NGOs and Government. Engineering procedures determine specific water use. Fixed water rights sold by Government. Farmers seen primarily as irrigators.	Principle of subsidiarity allows rangelands to be managed by pastoralists determining their best strategies of sustainable use.	Subsidiarity allows irrigators to develop own water management in irrigation systems and across the catchment for multiple purposes. Technology, water rights and access to land and water negotiated continuously. Farmers have multiple livelihood strategies.

Implications for irrigation and river basin management (selected examples)

Approach	Equilibrium	Non-equilibrium
Water rights and legislation	Fixed rights, quantitatively ascribed, added up until they 'match' a given supply.	Proportional water rights with quantitative and proportional caps.
Irrigation intake design	Irrigation centred, fixed, quantitative, dependent on crop water requirements being calculated—leading to non-proportional cross weirs.	Resource centred, emphasis on flexibility, continual adjustment of abstraction and proportional allocation.
Institutional strengthening	'Train farmers to manage water better'; predominantly with a focus on water user groups in individual irrigation systems.	With farmers, explore skills in whole catchment problem identification, negotiation and conflict resolution both between themselves and between them and higher level service providers; develop river user groups and apex bodies.

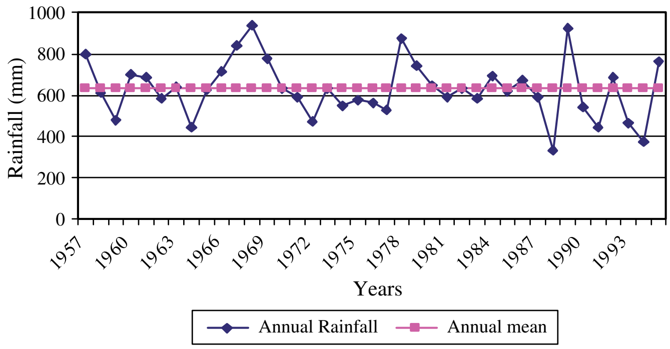

Fig. 1. Long-term annual rainfall for the study area (*Source*: Machibya, 2003, p. 89).

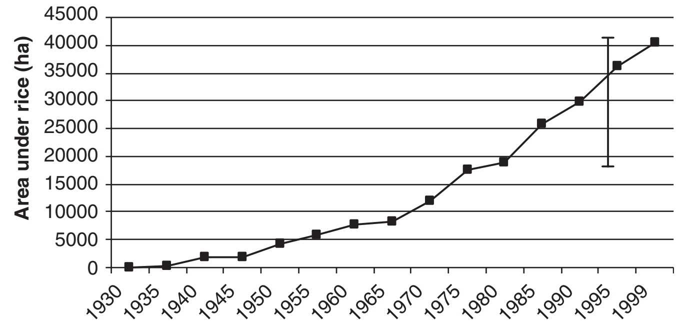

Fig. 2. The growth of rice in Usangu. The red line indicates the extent of variability in area under cultivation from wet to dry years (SMUWC, 2001, adapted).

and 30%.[2] Consequently, local farmers readily distinguish 'wet' and 'dry' years (Machibya, 2003), and experience considerable variability of water over small distances (Beale, 2004).

The variability and unpredictability of water supply is not only determined by exogenous climatic patterns and by the availability of potentially irrigable land in which irrigated land expands and contracts, but also by hydrogeology, which mediates the hydrological and irrigation response to rainfall. The majority of dry season flow in Usangu is found in four larger perennial rivers, fed from base flows in the high catchment. However, most rivers in Usangu are seasonal, and are not maintained by aquifers (SMUWC, 2001). The volume of water held in the semi-permeable sediments of the Usangu plains is insufficient to recharge rivers to assure a perennial flow. This is typical of African savannah plains; that while there are groundwater resources, these may often be unavailable, insufficient or separate from river-flow systems (FAO, 1995). Water for irrigation comes from surface sources and is thus more prone to variability and seasonal change than may be the case on the floodplains of Europe or Asia, where rainfall may be variable, but where rivers or irrigated areas are more stable, commonly maintained by groundwater. These issues are picked up again in Section 2.3.

The parallels of savannah irrigation to the rangelands debate hinge on the fluctuation of irrigated area from year to year in response to rainfall. SMUWC (2001) analysed the irrigated area in Usangu and found that it varied according to rainfall. Using aerial photography taken in an exceptionally 'dry' year in 1997–78, the project identified 9300 ha as 'core' areas which could always be irrigated and 44,500 ha in an exceptionally 'wet' year (1998–89). The finding of the 'core' being about 20% of maximum was verified with community surveys. Fig. 2 shows that variation alongside the historical growth of irrigation. Machibya's (2003) study on the large-scale Kapunga scheme similarly also found a variation between dry years (3829 ha in 1999–2000) and wet years (5429 ha in 2000–01), this variation is smaller due to a greater security of supply from the perennial Ruaha river.

Both 'small' and 'large' irrigation systems alter in size in response to supply with growth occurring down the gentle slopes of the alluvial fans and onto the plains via an extension of both canals and field-to-field watering. This paper contends that such dynamics are part of an intrinsic livelihoods/landscape response to climate variability rather than, particularly during contraction periods, a failure of technology to provide the right amount of water.

2.2. Livelihood dynamics of irrigation in Usangu

The change in area of irrigation raises issues of *how* this expansion and contraction takes place. In areas where land pressure is low, irrigation can dynamically adjust to take advantage of changes in water conditions, but in other areas due to mediating circumstances (e.g., land tenure, wealth and location on the system) this strategy is less available. Rather, the impact of water variability on economic and ecological systems is seen in broad shifts in livelihood strategies and farming systems to take rural households through periods of water scarcity.

Where unrestricted by other factors, the process of land preparation, tilling, weeding, wetting up, planting nurseries and transplanting seedlings is protracted over several months allowing many opportunities for an evaluation of water availability and readjustment of farming practices. In responding to supply, a farm may change in size dramatically as illustrated in Fig. 3, an example taken from the lower part of a catchment in the Usangu. In addition, on-farm employment (e.g., planting, weeding) increases as total area increases, so that one farmer might be concurrently cropping her own land, renting another plot and working on another's land.

However, these dynamics do not always apply, because the change in area of an individual farm depends on location, river size and local water supply. There is competition for land close to intakes where water availability is good. Here, control of land is generally inflexible, governed by money, prestige and time occupied. Those with land at the top end of the irrigation systems and top

[2] Conway, D., pers. comm., 2005.

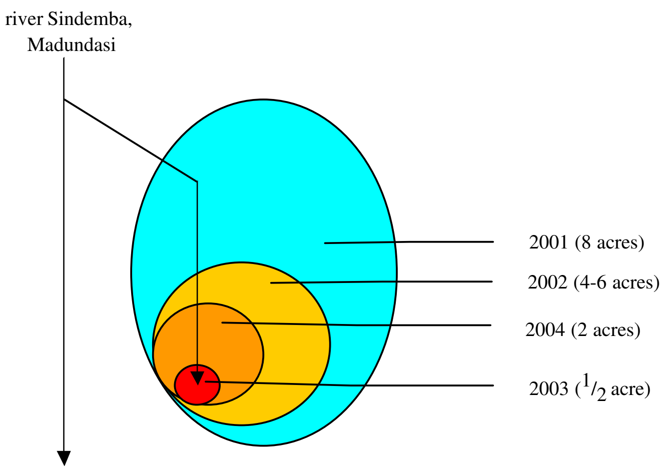

Fig. 3. Change in area for a case study farm in previous 4 years, lower Usangu (Beale, 2004, p. 31).

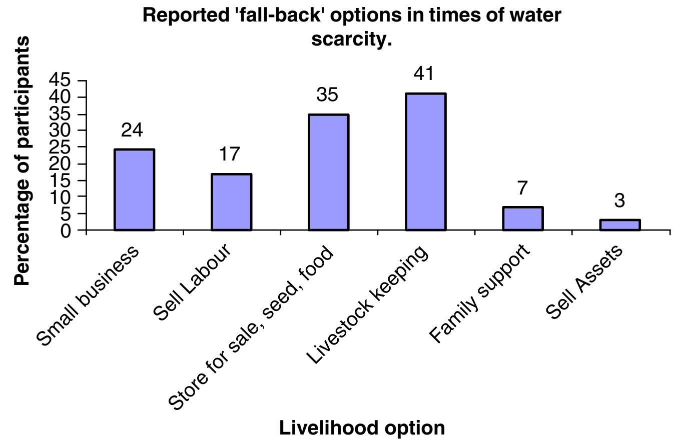

Fig. 4. 'Fall back' options in times of scarcity in the Usangu catchment (*Source*: Beale, 2004, p. 41).

end of the rivers in the more humid higher catchments tended to report little adjustment in area irrigated, verifying the idea of a fixed 'core' likely to be irrigated regardless of the availability of water on a larger scale. In contrast, poorer farmers at the peripheries of irrigation systems are forced to drastically reduce irrigation or abandon land in response to water shortage, often mid-season after the land has already been transplanted if the rains and river flows are intermittent (Beale, 2004). Some expansion of irrigation may occur in a linear manner through utilisation of paddies at the edges of the irrigation systems in wet years by farmers who already have land elsewhere; however, this is limited by capital to invest in land, seedlings, labour and, importantly, time and their availability in remote rural communities, and is thought in practice to be rare (Beale, 2004). The non-linear nature of irrigation expansion and contraction is exacerbated by local topography: in times of scarcity, small differences in the height of the land relative to water flows in irrigation canals are crucial in determining the pattern of land use, often leading to a fragmented mosaic of wet and dry paddy mini-basins disrupting the passage of water through the irrigation scheme, restricting supply to more distant *vijaruba* (small bunded paddy plots).

However, examination of the responses to water shortage reveals a more diverse and complex picture of vulnerability than a simple change in irrigated area (see Fig. 4, catchment-wide figures). Rather, a 'dry' year may lead to change in the farming systems and the rural economy to cope with reduced water supply. In particular, the asset and capital-rich farmers of the upper and middle catchment areas were often able to reduce their dependence on water supply by planting smaller *bustani* (vegetable gardens) and drought-tolerant crops, and increasing reliance on livestock. With good access to capital and markets, economic diversification is both a wealth-generating strategy for the better off, and a coping strategy for the poor in response to water scarcity. Richer farmers are able to migrate or commute to areas with greater water availability, engage in trading, find employment or gain access to loans in response to water scarcity and crop failure and supplement their reduced food supply with alternative incomes. In one research site in the upper catchment, a small credit union was providing credit for a range of investments, from farm inputs and livestock to building warehouse to allow storage of rice during market slumps and buying a truck to give farmers access to markets in Dar es Salaam.

Farms in the drier lower catchment areas experience greater rainfall variability, and like farms on the fringes of irrigation systems throughout the catchment, are vulnerable to heavy use of water by irrigators further upstream. Adaptation is less possible, and the diversity of livelihood and coping strategies is different and narrower. Trading, loans and saving are available only in very limited capacity, inaccessible to most. Aridity and seed costs restrict the capacity to plant *bustani* gardens, and there is increased reliance on marginal rainfed agriculture. Competition over water resources leads pastoralists to water cattle in the perennial wetland (a practise currently restricted due to its gazetting under Game Reserve legislation). Wholesale collapse of farming is a distinct possibility in these circumstances, as illustrated in the 2003 dry season, where drought caused outright crop failure, and one village in the middle catchment failed to harvest even small quantities of rice. Migration for work is a common coping strategy, and there was evidence of significant out-migration from villages in the lower catchment following the 'dry' year 2003 (Beale, 2004).

Thus, interannual variability of water is a critical driver of patterns of livelihoods and farming in Usangu. Irrigation might be regarded as opportunist, supplementary to rainfed agriculture, providing a cash income over subsistence production (SMUWC, 2001). Irrigation can be abandoned in times of drought with minimal disruption to well-being in the longer term, when years of water abundance provide a surplus that sees farmers through water scarcity. However, this ability to revert to subsistence agriculture is increasingly undermined, firstly, by migration to areas of water abundance, leaving the poorest without established subsistence farming systems, alternative land for rainfed farming or entitlement to grazing and, secondly, by the increasing commercialisation of the rural economy (Ellis and Mdoe, 2003; David, 1995) that encourages farmers to specialise in irrigated agriculture, again removing them (and their employees) from subsistence agriculture. Opportunist irrigators in Usangu are often highly transitory, without secure land tenure or water rights, and with few fallbacks if irrigation does not provide income, and consequently, irrigation systems see soaring levels of conflict, theft and even violence over access to water (Beale, 2004; Gaussen, 2003), leading to increased water use during critical states of water scarcity, as farmers resist having to downsize and try to maximise production.

The on-going human cost of water scarcity has a direct impact on the capacity of farmers to adapt to water variability. If cash crops or seed stores are used to compensate for food shortages, this has a knock-on effect on available resources and capital for investment, reducing the capacity to farm the following year, even if water availability is good (Beale, 2004). A dry spell may also directly affect drinking water, and resources may be used for buying water from upstream, while drinking contaminated or stagnant water from irrigation run-off commonly leads to serious hygiene issues, especially for women and children (Beale, 2004; FNPP, 2003).

In summary, the impact of water supply variability is seen throughout the rural economy, as households rely on the bio-physical and economic abundance of wet years to build resources of food, seed or money to carry them through the dry years. However, women, economic migrants, those at the tail-end of irrigation systems and catchments and those who are reliant on cash incomes from commercial production are often without the capacity to adapt their farming systems and livelihoods, reducing the resilience of both the economy and farming systems to water variability.

2.3. Concepts of resource sustainability

Common definitions of sustainability argue for "the management of natural resources to ensure their continued capacity to be productive in both agricultural and environmental capacities" (AFFA, 2000). This utilises the concept of states and thresholds, where below a limit, the resource is unable to generate, renew or protect itself. For example, erosion accelerates when soil is bare, fish stocks are threatened by over-fishing of viable adults and overgrazed grassland does not re-seed itself. The resource moves across thresholds from self-renewing to exhausted. Here, sustainability is about protecting 'natural capital' (Costanza and Daly, 1992) and preventing the degradation of the resource by defining use levels that match capacities within a particular state as well as defining use levels that recognise the dangers of transition across the thresholds that exist between states, the general aim being to stop a transition to a point where the resource collapses.

In non-equilibrium ecology, the conception of sustainability changes as the 'crossing' of thresholds is recognised as a normal and recurring event. Non-equilibrium thinking suggests that the relationships are inherently dynamic over several scales, and that trends over time are not linear, impacts are variable and an 'end-state' is not discernable. One way that the notion of sustainability of resource use in non-equilibrium ecology is defined is via transitions of utilisation through the geographical dimension. In pastoral systems, grazing shifts from place to place often following rainfall, leaving 'overgrazed', 'degraded' places to replenish themselves. Similarly, shifting cultivation maintains sustainability over a landscape, through the presence of several patches at different stages of succession. Thus, boundary issues are crucial to management strategies that observe sustainability over large time scales and several locations or whole landscapes. Holling and Gunderson (2002) and Suding et al. (2004) redefine ecosystem vulnerability around adaptive resource cycles, measuring it in terms of how much disturbance can be absorbed before the structure and behaviour of the system changes, e.g., shifting to an alternate state or re-stabilising around a different equilibrium. Such arguments suggest that we need to be less certain about our value-based assessments of 'degradation' and 'sustainability'. In situations where ecosystems are best characterised as non-equilibrium, thresholds that differentiate 'sustainable' and 'unsustainable' use have a qualified meaning.

Regarding water, notions of demand and supply management provide one way of exploring sustainability. Demand management means reducing demand to meet levels of supply, in contrast to supply management which means boosting supply to meet increasing demands. These responses rely on the concept that sustainability is about matching demand with supply, either at parity or some other managed ratio. Thus, the resource is sustainably delivered when supply matches or is greater than demand.

The sustainable management of groundwater resources is commonly based on this concept of 'matching' abstraction to long-term rates of replenishment or recharge, unless mining of the groundwater resource is specifically sanctioned (Grimble et al., 1996, Sophocleous, 2000). Over-abstraction can lead to a physical partial collapse in storage capacity or to intrusion by saline waters. Thus, groundwater requires a version of resource protection.

'Matching' can be applied to surface water resources that are less variable around a steady state, either because of groundwater, artificial storage or a temperate climate. Because the surface resource is predictable, we can define levels of use that match supply that do not lead to excessively dry rivers. However, for two reasons a 'matching' concept of sustainability does not apply to surface water resources in savannah Sub-Saharan Africa. Firstly, at the river basin level, the source of the resource is exogenous to the system, so that overuse does not necessarily via a feedback loop undermine potential for re-supply. Surface water resources are 'renewed' rather than internally 'renewable'. A river basin that completely dries out in a drought can flood the next year. The river basin opens and closes for a wet and dry year, respectively.

Secondly, it is difficult to determine *predictable* levels of supply and demand for planning and management purposes. Without buffering provided by aquifers or large-scale storage, supply is highly variable due to climatic conditions. Furthermore, demand is strongly coupled to supply; as supply increases, so does withdrawal and depletion. It is the high *irrigable* area found in savannahs, combined with increasing populations and access to markets, that gives rise to a very high potential water demand that might only be met in very rare wet years or after a sequence of wet years. Given appropriate farming systems in the vicinity, water demand mirrors supply; increasing in a wet year as the cropped area increases and decreasing in a dry year. In Usangu, additional ability of users to 'soak up' supply arises from an expandable wetland and from the large Mtera reservoir that can be refilled. This coupling is demonstrated in Fig. 5, where the right-hand graph shows a theoretical trend over time towards a closed river basin at equilibrium with demand matching supply. In the left-hand graph, demand fluctuates with supply (although demand expectations remain constantly high), and rarely is an equilibrium point met when a specified demand can be brought up or down to a static predictable supply. The implication here is that balancing or matching at the river basin scale is more problematic.

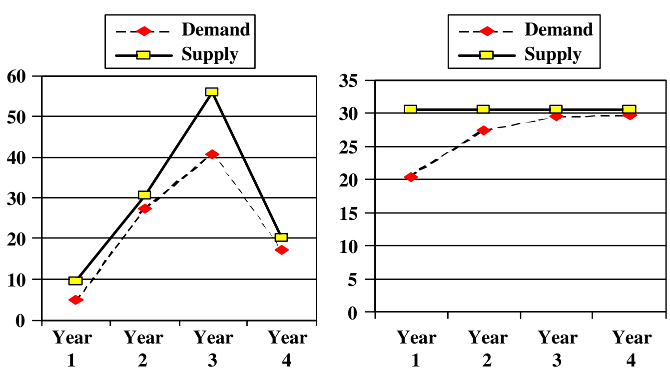

Fig. 5. Contrasting dynamic and static balancing of demand and supply.

3. Implications for irrigation and river basin management

This exogenous, non-buffered, highly dynamic supply, that is quickly mirrored by demand, makes fixed, preset 'matching' of demand to supply difficult to apply. If demand levels cannot be set to match supply, what does this mean for sustainable river basin management? Although in this paper we contend ourselves with the water management aspects of this, we argue that sustainability in the context of a variable water supply also stems from economic resilience; of livelihoods based on the general development of ecosystems, agriculture, industry and the economy—in other words, maximising the flexibility of a system so it is less likely to reach breaking point.

We begin by modelling a river's supply as a flow frequency diagram (Fig. 6). This reflects a generic variable regime, with small flows exceeded much of the time and larger flood flows prevalent but less frequent. The chart is divided into three phases or 'states'; bulk water that covers high flows that are rare but significant in volumetric terms; medial/scarce water that binds the median flow; and critical water that comprises very low flows. The chart depicts two lines; one of a wetter basin with a higher frequency of larger flows and the other (the lower line) of a drier basin with low flows being more commonplace. Each state in each basin has specific functions, management goals and challenges. Bulk water during the wet season tops up natural and artificial storage bodies and can both flush and deposit detritus and sediments. Medial water has to be

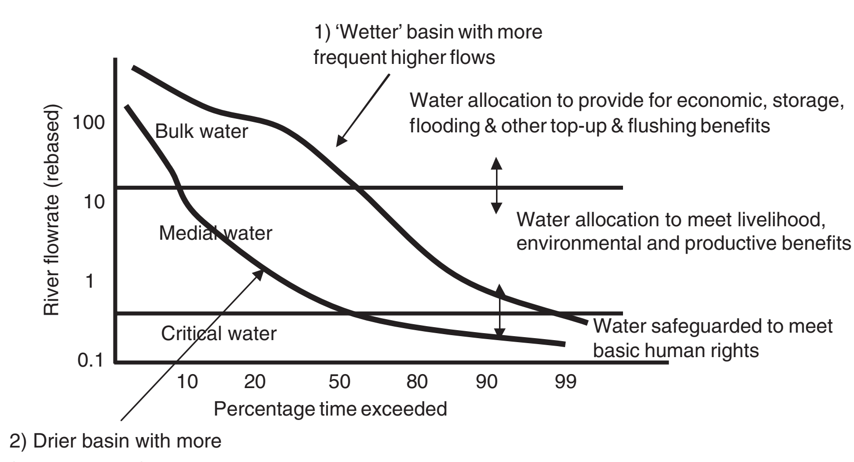

Fig. 6. Flow frequency chart to depict three states of water supply.

shared between sectors for environmental, urban and agricultural functions. Critical water is for vital lifeline, health and domestic purposes.

The 'sustainability' objective is to formulate interventions that store, save, allocate and distribute water to generate specified functions and outcomes across and in each of the three states in the face of continual movement of the river basin across the three states. For example, in moving from the medial state to the critical state, infrastructure and institutions are required to distribute small amounts of water, so that agreements and structures that function for the higher flow medial state do not exacerbate shortages and conflict by continuing to be applied during the critical state. Moreover, infrastructure and institutions within a state have to be designed to recognise the nature of water abstraction in that state. To exemplify this discussion further, we turn to three interrelated issues related to the management of water for irrigation primarily in the medial state, but also attending to water in both bulk and critical states.

3.1. Water legislation and rights

Current abstraction licensing[3] in Usangu is founded on fixed water rights sold as quanta (e.g., 200 l/s) provided by an 'improved' intake design (World Bank, 1996). The formal water rights are poorly matched to the problems encountered in these river basins (van Koppen et al., 2004), primarily because they are the results of a perception that a predictable set or average level of supply exists, so that demands may be allotted to users at a fixed rate. In practice, water supply is highly variable; an allocation accurate during a good wet season may be inappropriately excessive another time. Moreover, an 'average flow rate' is a statistical construct rather than a common condition. There are some mechanisms to alter the abstraction rates according to water availability, but these are bureaucratic and complex, and in practice do not work fast or comprehensively enough to be effective. Administratively, the water rights are particularly difficult to update in the light of a constantly changing situation.

A new 'legal-infrastructure framework for catchment apportionment' (LIFCA) (Lankford and Mwaruvanda, 2006) for managing formal and informal rights and river basin infrastructure adopts the viewpoint that the supply side is inherently dynamic. It does this by rationalising the interface between formal water rights (that establish a so-called wet season 'volumetric cap') and customary agreements that relate to negotiations over shares of in-stream water (the dry season 'proportional cap'). The framework utilises the three-state understanding of the water supply and incorporates existing formal water rights for the purposes of capping abstraction to ensure basin-wide allocation objectives are met during the bulk state part of the year—the peak of the wet season. Thus, it should be noted that the ability to increase demand when supply allows (which maximises economic utility) does not sanction an uncontrolled expansion of upstream user abstraction capacity, because bulk flows have useful downstream functions[4] during these 'pulse' events. Capping irrigation abstraction 'forces' downstream allocation during the bulk state.

Secondly, LIFCA demonstrates how, if strengthened and supported, local customary negotiations combined with infrastructure interventions, might help set and relate to the proportional cap of water abstraction that applies during the medial flow state (i.e., parts of the wet season when flows are low). The next section on intake design presents this discussion in more detail.

Thirdly, with regards to the critical state, the framework suggests that water supplies are provided during the driest part of the dry season either via boreholes, pipe networks or via the cessation of shares of abstraction in favour of retention of water in the river so that it may be collected by hand. Rangeley (1985) observed this many years ago (p. 9): "as with all ephemeral streams in arid zones, these watercourses offer little protection for irrigation when their limited flows must be devoted perhaps exclusively to human and livestock supply."

Capping the maximum total abstraction levels (a bulk water determinant) assists in the management of proportional division during the medial state and water provision during the critical state. Expansion above the current total abstraction of 46 cumecs increases the marginal propensity for each intake to abstract small amounts of water during the dry season, cumulatively drying out the river system, and requiring disproportionately more control and policing to manage the system. In other words, a large total abstraction sensitises the whole river system to drying out during low flow periods. This exemplifies how objectives and practices in one state impinge on objectives and provision of water in other states.

The LIFCA framework explicitly designs other dimensions around the wet/dry season flux to assist rather than undermine these legal pluralisms and water allocation objectives. Thus interventions in the area of irrigation can be guided to two main areas, firstly, that of intake and canal design and, secondly, that of institutional strengthening.

3.2. Irrigation infrastructure design

We believe that conventional irrigation engineering is generally a modernist intervention within a paradigm of

[3]Subsidiary legislation (Government Notice No. 347 of 1994 under section 38(2) of the Water Utilization (Control and Regulation) Act No. 42 of 1974).

[4]Replenishing wetlands, aquifers and springs; flushing and depositing silts for riverine and delta ecologies; and refilling Mteru and Kidatu hydropower dams.

equilibrium and steady biomass accumulation. As Adams (1992) argues, these are political attempts to exercise control over rural areas and unpredictable natural ecosystems. While it is not controversial to argue that water shortages are central to the performance of irrigation investment projects in Africa (Rangeley, 1985; Adams, 1990; Moris, 1991; McCully, 2001), the idea of non-equilibrium as definitive of semi-arid savannahs implies that irrigation systems should be able to adjust to variations in water supply, rather than overcome them.

In Usangu, water downstream is contingent on how upstream water is appropriated in relationship to the exogenous variable supply. Conventionally 'improved' irrigation intakes allow the withdrawal of all the river water beneath the maximum capacity of the intake, so that with decreasing river flow, upstream abstraction proportionally becomes larger and larger, eventually drying out the river (Lankford, 2004b), as depicted in the left-hand side in Fig. 7. Conventional intakes attempt to fix a supply to the irrigation command area, yet aggravate a delicate situation where dry season flows of less than 100–200 l/s have to be shared between many users.

A non-equilibrium solution is to establish abstraction patterns that change as supplies change (Lankford, 2001, 2004a, b). A proportional approach (depicted in the right-hand side in Fig. 7) follows the fluxes in supply, dividing water according to pre-arranged or adjustable shares. Proportional dividers more commonly found within irrigation schemes to split water flows into shares (Plusquellec et al., 1994), including in Usangu, could be adapted to riverine intakes to enhance the manageability and transparency of division. The key difference, therefore, between equilibrium and non-equilibrium design is the latter's use of proportional dividers to share water abundance and drought much more equitably down the river. This means that the uppermost intakes would receive less water, invoking new institutional challenges of managing water at the catchment scale.

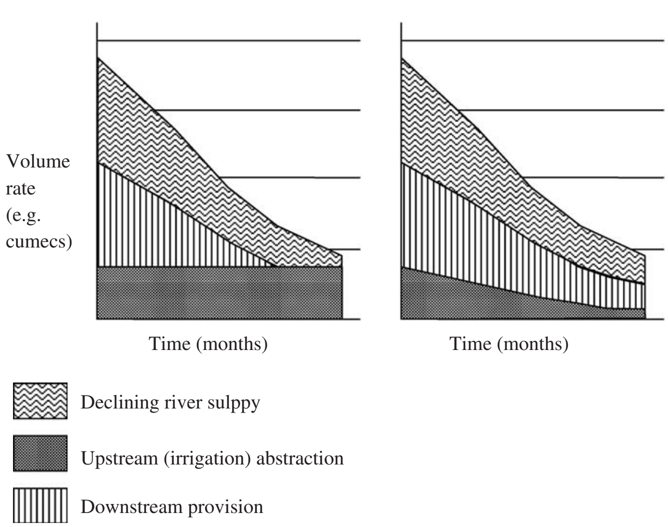

Fig. 7. Fixed and proportional upstream abstraction with declining supply.

3.3. Institutional strengthening at the basin scale

Research identified evidence of institutional capacity in Usangu to dynamically adjust irrigation practices to variability in water supply. Actions include the timetables to schedule and distribute water more equitably across systems; fines and temporary bye-laws to prevent water theft and water blocking, use of the village executive committees to mediate conflicts, collective canal cleaning, alterations to in-field water control and limiting cultivation to certain areas of an irrigation system in dry years to prevent crop failure (Machibya, 2003). Similarly, as discussed in Section 2.2, factors such as seed availability, market access and capacity to revert to subsistence agriculture have a demonstrable impact on reducing dependence on water resources for livelihood security. Thus, farmers have a flexible and practical relationship with systems of water management. Similar to historical studies on indigenous irrigation in Tanzania and Kenya (Adams and Anderson, 2002), the evidence in Usangu suggests that rules, management systems and even entire irrigation systems are adopted and discarded, as required by irrigators, who are capable of integrating several approaches with very different histories and cultural meaning into the management of water and conflict (Cleaver, 2001).

Of particular interest is how to strengthen this institutional capacity to cope with, and adapt to, water variability and unpredictability. The potential for adaptation within farming systems and rural economies may significantly increase resilience to water variability. However, we argue that institutionally allying this capacity to individual small-scale systems may miss the imperatives associated irrigation systems where they have coalesced into a meta-system. This raises issues of communication over wide distances and democratic participation in water management (Wester and Warner, 2002). While government institutions argue that irrigators should receive training on water management (MAFS, 2005), evidence amassed by studies in Usangu illustrates that farmers are deeply immersed in the problem of managing water across a series of constraints and are experimenters in, and observers of, their practices. The objective is not to tell irrigators how to irrigate, but to offer safe spaces for explorations in water sharing across the basin (Lankford and Watson, forthcoming) to provide a means for farmers from different systems to engage more constructively with each other and with service providers (e.g., Basin Officers). For example, arising out of the workshops, farmers have initiated a river 'apex' group to manage relations between upstream and downstream users in the Mkoji subcatchment in Usangu.

4. Conclusions

Studies in Usangu observed that water resources managed according to conventional 'threshold' theories of sustainability grounded in discourses of ecological equilibrium tended to exacerbate water shortages, especially for disadvantaged downstream users, including poorer farmers and the environment, while non-equilibrium principles would possibly generate alternative means of sharing water. While there are basins that have similar patterns of water supply and demand in Sub-Saharan Africa, (e.g., Pangani in northern Tanzania, Mara in Kenya and the River Niger), parallels can be drawn with other river basins in the tropics and sub-tropics that are experiencing increasing levels of demand that outstretch supply, which enhance the behavioural dynamic in wet and dry years. Moreover, once aquifers under floodplain basins in South Asia become nearly depleted, the irrigation response will be to surface rather than sub-surface water availability, which brings those floodplains closer into line with savannah plains that lack groundwater buffering. Given this wider reference, the paper argues that an alternative understanding of sustainable management of irrigated river basins should be informed by non-equilibrium thinking. This incorporation might generate more cautious and effective departures in water management strategies and procedures:

Firstly, where irrigation has grown and coalesced in scale to dominate water abstraction in a river basin, we can re-evaluate the dialectic of small- versus large-scale systems as a means to interpret irrigation. Furthermore, one implication of a greater merging and mirroring between the behaviours of irrigation systems and river basins is that integrated basin management should treat irrigation as a key determinant of water behaviour, rather than as an autonomous sector or component.

Secondly, the water distribution dynamics associated with African savannah irrigation suggest that equitable and secure entitlements to water resources are linked to patterns of areal expansion and contraction. Although beneficial expansion in wet years is widely possible, contraction during drought is highly inequitable, providing 'protected' water to a minority. It is this contraction that places additional burdens on managerial goals of equity, increasing demand for water during the most critical times of water scarcity and reducing the capacity for rural economies to cope with climatic variability.

Thirdly, this illuminates the assumptions that underpin current water allocation frameworks in accommodating hydro-metrological variability. While technological interventions can bring greater water control in times of abundance, in times of scarcity some interventions are inadequate at manipulating limited flows and inflexible to the changing needs of farmers, monopolising scarce resources at times of most need and contributing to conflict. We recommend that during the medial state, proportional abstraction might be suitable in apportioning water, including to the environment. This may require co-programmes to ensure success; modified water rights and designs of intakes; a focus on critical water needs to provide vital safety nets to people, livestock and ecological systems during drought; capping of the maximum total abstraction to pass more water downstream in times of bulk flow; and institutional work to mediate water sharing.

Fourthly, although not discussed in the paper, the analysis throws caution on the theoretic that water management may be improved if economic signalling is introduced (c.f. the Dublin principle of water as an economic good). Costing for water may be feasible, if problematic, where appropriate technology is installed, but where supply is unpredictable the concept that users will pay for water that cannot be guaranteed at a given supply level seems particularly untenable. Moreover, it is how pricing water facilitates the transition of water users to different levels of usage when supply changes that becomes the germane question under non-equilibrium thinking.

Lastly, the functions of more water storage in Sub-Saharan Africa (the subject of renewed donor discussion (World Bank, 2003)) might gain from attention given to the use, variability and manageability of water within and across all three states of the water supply regime. There is evidence that shortfalls of power from the Mtera and Kidatu reservoirs arose from the desire to maintain a consistently high electricity output in the face of a variable supply (Yawson et al., 2003). 'Non-equilibrium' questions storage because of the lack of prediction of an outcome for a given input, echoing concerns of Zimmerer (1994). One preoccupation with scarcity in hydraulic terms is the provision of infrastructure that volumetrically enhances productive supplies during low-flow periods; aiming to maintain medial-type flows during a critical state. Yet, storing and using such water requires ideal conditions and appropriate frameworks of allocation. Irrigation duties of more than 1.0 litres s^{-1} ha^{-1} imply substantial storage to remove the uncertainty associated with drought, while evidence from Usangu suggests that if demand is nearly open ended and has few upper limits placed on it, storage creates a situation akin to a wet year, where demand rises so that supply once again is deemed insufficient. It is the coupling of demand to supply that creates risks for vulnerability rather than equilibrium shortfalls between 'set' levels of demand and supply. In addition, stored water has downstream functions across all three states not only in supporting medial continuity. Such cross-state functionality is on the increase, both volumetrically and in terms of complexity of delivery, implying that storage might be more valuable augmenting a bulk-state pulse event such as a flood for environmental benefit, or cushioning a transition to a critical state when released for lifeline needs during droughts rather than being used for irrigation.

Summarising, in closing river basins with increasing areas of irrigation, 'small-scale irrigation', with connotations of user friendliness, ownership cohesion and consensual management, no longer provides the foremost entry point for analysis and characterisation. Rather, we need to comprehend irrigation collectively across a landscape or basin, and examine in more detail the dynamic, adaptive behaviour associated with pulse-driven non-equilibrium natural resource ecosystems. A more complex and subtle meshing of technology, institutions and management is required that recognises the potential discord between these in areas where water variability and competition are both notably high. Overall, we conclude that sustainable management of variable water resources needs to be grounded in an understanding of the impacts across a river basin; be based on decreasing sensitivity and increasing resilience to water shortage in livelihoods and ecosystems; and continue to see and support water management at the local scale from the viewpoint of closely involved users, while at the same time establishing frameworks at the basin scale that recognise water variability, multiple demands and the manageability of transitions between states of water supply. Facilitating transitions closely adheres to the notion of transformability (Walker et al., 2004) as a determinant of resilience in sustainability.

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