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**Article — Published Version**

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Environmental Research Letters

**Provided in Cooperation with:**

Leibniz Institute of Agricultural Development in Transition Economies (IAMO), Halle (Saale)

*Suggested Citation:* Amirova, Iroda; Petrick, Martin; Djanibekov, Nodir (2025) : Evolving institutions of sustainability: A dynamic model of historical water governance transformations in Central Asia, Environmental Research Letters, ISSN 1748-9326, IOP Publishing, Bristol, Vol. 20, Iss. 11, pp. 1-12, <https://doi.org/10.1088/1748-9326/ae137c> , <https://iopscience.iop.org/article/10.1088/1748-9326/ae137c>

This Version is available at:

<https://hdl.handle.net/10419/335909>

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ENVIRONMENTAL RESEARCH  
LETTERS

## LETTER

## Evolving institutions of sustainability: a dynamic model of historical water governance transformations in Central Asia

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## OPEN ACCESS

## RECEIVED

15 March 2025

## REVISED

3 October 2025

## ACCEPTED FOR PUBLICATION

15 October 2025

## PUBLISHED

28 October 2025

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**Abstract**

This article introduces evolutionary game theory as an approach to stylised long-term analysis of water governance transformations in Central Asia. This world region has been strongly affected by natural hazards, political disruptions and historically diverse attempts to establish effective water management principles. Drawing on historical and contemporary evidence, we establish a game theoretical baseline model of a user community in which irrigation is efficiently governed by group sanctions. By allowing for drift in the evolutionary equilibrium, we model how a loss of traditional authorities over water management can erode established group norms. We then analyse a hypothetical scenario of privatised water rights, inspired by historical and current policy debates in Central Asia. Under the assumption that such rights can be technically implemented, we show that they can restore an efficient water use equilibrium of owners that is egalitarian and evolutionary stable. We discuss how future climate change scenarios or conflicts over transboundary water allocation may affect the model results, focusing on the effects of increased uncertainty and of decreasing water productivity on system resilience. Productivity shocks may make low-performing equilibria unsustainable and thus lead to disruptive change or extinction of certain equilibria. Policy should focus on local interaction as an arena of institutional change. We suggest empirical research questions emerging from our analysis and highlight the benefits of uncontested property rights as an institutional solution to water governance.

**1. Introduction**

The ever more present risks of climate change have underscored the need for resilient governance mechanisms that protect natural resource user communities from extreme weather events or man-made calamities. As academics and policymakers increasingly understand, natural resources are governed by complex social institutions embedded in larger environmental and political systems. Apart from occasional punctuations like disasters or revolutions, such systems follow slowly moving trajectories that are often hard to influence by day-to-day policy measures. Drawing on case studies from Chile, South Africa and Uzbekistan, Herrfahrdt-Pähle *et al* (2020) usefully reviewed the potentials of ‘windows of opportunity’ for massive socio-political transformations of

natural resource governance. They also stressed the multiple societal levels and the sequence of phases to be considered in such change.

Yet despite an emerging literature on the governance of sustainability transformations, finding both workable and fruitful analytical frameworks to resolve the behavioural patterns of interest remains a challenge. While theoretical approaches to modelling human behaviour are many, connecting them to real-world applications of natural resource transformations continues to be demanding (Schlüter *et al* 2017). Here we introduce evolutionary game theory as a novel approach to reducing complexity while addressing key desiderata of modelling resource system transformations from a social science perspective. We take the long-term water governance transformations in Central Asia as a motivating case,

located in a world region strongly affected by natural hazards, political disruptions and historically diverse attempts to establish effective water management principles (O'Hara 2000, Abdullaev and Rakhmatullaev 2015).

Like Herrfahrdt-Pähle *et al* (2020), we study the relation between radical political change and governance transformations. But unlike the multi-level analysis by these authors, our analytical approach zooms into an arena of specific resource governance regimes maintained by small groups of resource users. We employ historiographic evidence to inform a well-specified behavioural framework of game-theoretic modelling and simulation of a stylised water user community exhibiting features of real-world Central Asia. Our evolutionary resource user model inspired by Bowles' (2004) study of the prehistoric property rights revolution enables us to reconstruct institutional dynamics during different historical governance epochs: pre-Tsarist, Tsarist, and Soviet. Our approach formalises the interactions among water users and highlights the effects of different governance strategies on resource allocation and social efficiency. It thus avoids simplistic normative categories such as 'corruption', as demanded by Obertreis (2017, 22), and replaces them by structural analysis that can inform the role of (central) government and stimulate new research questions for further historiographic and empirical research, as outlined below.

Our conception of governance follows Ouchi (1980) in distinguishing the three governance modes of markets (voluntary exchange of privately controlled goods or services), hierarchies (bureaucracies) and local communities (specified as 'clans' by Ouchi). As detailed by Bowles (2004, 473–501), this approach maintains the behavioural *a-priori* of methodological individualism while allowing for higher-level selection processes based on aggregate social outcomes. We show below how these governance modes derive their stability from different incentive structures, how they involve conflicts of interest and affect the distribution of payoffs, and react differently to external shocks. Thurman (1999, 2–9) refers to closely related governance modes as the basic categories in his historiographic study of irrigation in Central Asia.

Our analysis claims relevance for a region that is hydro-geographically often called the 'Aral Sea Basin' today (O'Hara 2000, 368–371, Peterson 2019). It includes the contemporary states of Kyrgyzstan, Tajikistan, Turkmenistan and Uzbekistan, as well as the southern provinces of Kazakhstan. The historical terms used for this region are 'Turkestan' or 'Middle Asia' (Peterson 2019, 9–11). While irrigation arrangements certainly display some local heterogeneity, the governance mechanisms examined here existed in more or less similar forms in all the major river oases of Central Asia (such as Bukhara, Khiva and Samarkand) as well as the Ferghana valley (Obertreis

2017, 29; 68), where they were also subject to similar forces of Russian conquest and Soviet authority.

## 2. How historical narratives of governance modes inform modelling choices in this study

Following Thurman (1999) and O'Hara (2000)<sup>4</sup>, we claim that Central Asian water governance prior to Russian colonisation was in many ways inclusive in the sense of Acemoglu and Robinson (2012), i.e. it allowed broad participation of the population in productive activities governed by transparent social norms. The historical networks of canals, which fed farms, villages, and towns, were constructed and managed locally by communities of farmers (dehqans). A mirab-bashi, the chief water master, coordinated the construction and maintenance of larger feeder canals (Morrison 2008, 201–243). Water user communities elected the mirab-bashi and paid his remuneration, depending on the satisfaction of dehqans concerning the irrigation service quality they received. Regular water managers, the mirabs, supervised the secondary canal maintenance, water allocation and distribution. They were also elected and paid by the dehqans. Water user associations (ketmans) comprised of three to four villages would have elected elders (aryk-aksakals) representing their interests. The election-sanctioning mechanism of pre-Tsarist water governance community thus expressed a civic-mindedness of the dehqans (Amirova *et al* 2022). Community institutions of residence self-governance (such as mahalla) with the capacity to produce many forms of public goods in water management emerged and prevailed (Dadabaev 2017, Brick Murtazashvili 2022).

Between the 1860s and the 1990s, the region was subjected to Tsarist Russian and then Soviet rule. The invading nations massively invested in the expansion of irrigated cotton production. Konstantin Petrovich von Kaufman, Governor-General of Russian Turkestan, disposed most of the incumbent water managers (Peterson 2019, 67–68). The central department in Tashkent appointed an 'irrigator', an assistant and a group of conductors to each province (Morrison 2008, 210). There existed a *de jure* election system, but such system *de facto* turned into state appointments. Thurman (1999, 249) reasons that the very election mechanism degenerated into sales of positions to the highest bidders.

<sup>4</sup> Our selection of historiographic sources is limited to the most relevant secondary work published in English language (see table 1). While most of the recently published studies referenced here take a decidedly critical approach to a Eurocentric, one-dimensional writing of colonial history, doing full justice to alternative views on the Central Asian past is beyond the scope of this article. See Gorshenina (2021) for an engaging account.

**Table 1.** Model elements and their historical analogues.

Elements in the model	Motivating historiographic and contemporary analogues
<i>Behavioural assumptions</i>	
Default strategy set: grabbing, sharing, punishing (civic)	Historical relevance of social norms in water allocation across Central Asia; historical evidence on group sanctioning of grabbers (Thurman 1999, O'Hara 2000)
Bourgeois strategy respecting private property rights	Hypothetical emergence of a class of water users accepting and defending private use rights; historical draft water legislation by Tsarist government (Morrison 2008, 235)
<i>Institutional equilibria</i>	
Group sanctioning (Rousseauian)	Pre-Tsarist election-sanctioning mechanism; institutions of residence self-governance (mahalla) (Dadabaev 2017)
Grabbing & wasting (Hobbesian): less efficient than group sanctioning, evolutionary stable	Endemic water seizure by farmers after Russian conquest (Thurman 1999, 249); 'irrational' water use during late Soviet period (Obertreis 2017, 359–365)
Private water use rights with efficiency restored	Hypothetical scenario based on post-independence IWRM policy agendas (Zinzani 2015)
Contested property rights	Contemporary evidence on incomplete reform implementation (Bichsel 2009, Petersen <i>et al</i> 2024)
<i>Out-of-equilibrium dynamics</i>	
Drift with ensuing tipping towards grabbing & wasting	Degradation (during Tsarist colonisation, Peterson 2019, 50–70) then collapse (during Soviet period) of communally sanctioned water allocation mechanisms (Dadabaev 2017); Soviet-appointed irrigators' loss of communal reputation (Obertreis 2017, 369)
Degeneration of group sanctioning; water users switch strategies from punishing to grabbing	Central appointment of irrigators makes communities vulnerable to grabbing; unlearning of civic-mindedness during Russian/Soviet colonisation (O'Hara 2000, Morrison 2008, 218–223)
Introduction of private water use rights with emergence of Bourgeois strategy accepting and defending these rights	Pre-Tsarist evidence under the Khanates (Thurman 1999, 68–70); hypothetical reform scenario
Contestation of property rights with ensuing invasion by Sharers	Post-independence privatisation struggles (Bichsel 2009; Zinzani 2015)

Source: Authors.

After the Bolshevik revolution and the foundation of the Soviet Union in 1922, despite political rhetoric of 'abolishing colonial chauvinism' (Obertreis 2017, 139), the rulers in charge promoted the bureaucratic approach to irrigation governance with unabated force and extended it to huge new areas of 'virgin lands'. During the Soviet period, problems of 'irrational' water use became widespread, i.e. the excessive consumption of irrigation water at the local level (p 359). Though several services were set up to control the water use in the 1960s, they could not change the ever-deteriorating unsustainability in water usage patterns. Instead, irrigators were constantly losing

their reputation and hence were not able to penalise the illegal water users (Obertreis 2017, 369). When the Soviet Union was about to collapse, the desiccation of the Aral Sea provoked worldwide reactions as one of the biggest manmade environmental disasters caused by misguided irrigation practices (Micklin 1988).

After national independence, international donors recommended or demanded the restructuring of farming and irrigation facilities, generally emphasising a more decentralised and democratically legitimised administration and private property in productive assets (Lerman *et al* 1996, Spoor

1998). Especially in the irrigation sector, governments and donors placed hopes on the introduction of 'Integrated Water Resource Management (IWRM)', stipulating the participation of water users in irrigation governance and the relevance of economic principles for effective water management (Zinzani 2015, Amirova et al 2019). Yet the effectiveness of these strategies has been quite mixed, considered by some as an outright failure (Veldwisch and Mollinga 2013, Herrfahrdt-Pähle et al 2020 on water management; Xenarios et al 2020 on the broader context).

In the following, we establish a baseline model of an irrigation community involving the interaction of three possible strategies of water governance leading to varying individual benefits and costs. We motivate a historical setting in which irrigation is efficiently governed by group sanctions based on a socially stratified society. Its informal hierarchy is then overthrown as appointed bureaucrats undermine the sanctioning systems. Alternatively, we explore the hypothetical introduction of private water use rights, also motivated by historical and contemporary evidence.

Table 1 summarises the behavioural assumptions and key outcomes of the model as well as their empirical analogues with historiographic references. Important aims of the model are not only to depict likely institutional equilibria, but also the out-of-equilibrium dynamics that make hydraulic societies move from one equilibrium to another. In our context, these dynamics illustrate how path dependencies may inhibit reform implementation or how ideal-type equilibria materialise only incompletely for long time periods.

### 3. The evolutionary model

#### 3.1. Key principles of game theoretical modelling

We analyse water governance outcomes according to the key principles of evolutionary game theory (Maynard Smith 1982). These are (a) the assumption of adaptive agents bearing behavioural rules (i.e. strategies) that are (b) being updated in a recurrent replication process according to their fitness (defined here by numerical payoffs), where (c) chance events may lead to behavioural innovations (mutations) that agents can learn via conformism or exposure. This allows the modellers to (d) explicitly study the population dynamics outside stable equilibria and thus trace evolutionary or historical processes in a sequence of time periods (Bowles 2004, 60–78).

In the following, we define an artificial community consisting of interacting water users bearing certain strategies implying individual payoffs (i.e. the behavioural assumptions in table 1). We follow the standard assumptions of payoff-monotonic updating, i.e. strategies with above-average payoffs are adopted by others and increase their share in the population. Moreover, we assume that individuals are paired

randomly to interact. At the beginning of each period, a fraction of the population updates their strategies by comparing it to a 'cultural model', which we assume is the most successful strategy in the community. If the cultural model and the individual employ the same strategy, it is retained by the individual, otherwise it switches its strategy to the more successful one.

The payoffs represented by the cultural model and experienced by the individual depend on the specific pairings in any given period and therefore vary with the population frequency of each strategy. Of key interest is whether any such frequencies lead to a dynamically stable equilibrium, in which case updating no longer leads to changes in the composition of strategies (i.e. the institutional equilibria in table 1). Moreover, we would like to analyse whether such stationary equilibria could be invaded by a 'mutation', i.e. an innovative strategy, thus leading to out-of-equilibrium dynamics as described in table 1. Populations that are able to repel such invasions are said to follow an 'evolutionary stable strategy' (ESS). Every ESS is a Nash equilibrium so that small changes in the population frequency of an ESS is self-correcting (Bowles 2004, 77).

#### 3.2. The baseline model of decentralised water governance

Suppose  $n$  members of a water user community are randomly paired to divide a water resource of value  $v$ . They can use three strategies: grabbing, sharing and punishing (the default strategies noted in table 1). Grabbing and sharing correspond to the Hawk and Dove strategies in the canonical model of competition for a scarce resource (Maynard Smith 1982, 11–20, Bowles 2004, 78–87). When Sharers meet, they divide the resource equally. When Grabbers meet Sharers, they take the resource. When Grabbers meet each other, they fight. With assumedly equal probability, they either get the resource or bear the cost of defeat,  $c > v$ . When Punishers meet Sharers or other Punishers, they divide the resource equally. However, when a Punisher is paired with a Grabber, all Punishers join forces and punish that Grabber. In case of victory, punishing water users share the water among all Punishers. In case of defeat, the punishing farmer bears the cost  $c$ . The probability of successful punishing the Grabbers is assumed to be the Punishers' population frequency,  $\beta \in [0..1]$  (Bowles 2004, 382–386).

Punishing, also called 'civic' by Bowles and Choi (2013a), is thus a collective strategy because punishing individuals support other Punishers who are interacting with Grabbers. Consequently, the success of a Grabber in an interaction with a Punisher depends on the number of Punishers in the community. This type highly values social norms (e.g. water sharing) and opts for punishing when that norm is violated. Table 2 summarises the narrative of the model and table 3 the resulting payoffs.

If the population frequency of Sharers ( $\alpha \in [0..1]$ ), Punishers ( $\beta$ ) and Grabbers always add up to one, the expected payoffs,  $\pi$ , for the three strategies are as follows:

$$\pi^{\text{share}} = (\alpha + \beta) \frac{v}{2}, \quad (1)$$

$$\pi^{\text{punish}} = (\alpha + \beta) \frac{v}{2} + (1 - \alpha - \beta) \{ \beta v - (1 - \beta) c \}, \quad (2)$$

$$\pi^{\text{grab}} = \alpha v + \beta \{ (1 - \beta) v - \beta v \} + (1 - \alpha - \beta) \left( \frac{v - c}{2} \right). \quad (3)$$

We use this model to study long-standing historical equilibria of group sanctioning in Central Asian water governance and the possible invasion of Grabbers due to the slow erosion of group norms in the course of Russian/Soviet colonisation (such as illustrated by the institutional equilibria in table 1). The simplex in figure 1 displays all possible combinations of the three strategies, where the fractions  $\alpha$ ,  $\beta$ ,  $\gamma = 1 - \alpha - \beta$ , indicated at the three vertices can be read off for any locus as the distance to the opposite edge (Bowles 2004, 384).

The vectors in figure 1 indicate the direction of movement in the region defined by the loci along which  $\alpha$ ,  $\beta$ ,  $\gamma$  are stationary (the thin lines within the simplex). The movements occur as a result of an updating of strategies. The updating process is monotonous in payoffs and follows a replicator dynamic as follows:

$$\frac{d\alpha}{dt} = \alpha \left( \pi^{\text{share}} - \bar{\pi} \right), \quad (4)$$

$$\frac{d\beta}{dt} = \beta \left( \pi^{\text{punish}} - \bar{\pi} \right), \quad (5)$$

where  $\frac{d\alpha}{dt}$  and  $\frac{d\beta}{dt}$  are the changes of the respective population shares over time, and  $\bar{\pi}$  is the average payoff to all three strategies, with  $\bar{\pi} \equiv \alpha \pi^{\text{share}} + \beta \pi^{\text{punish}} + (1 - \alpha - \beta) \pi^{\text{grab}}$  (Bowles 2004, 383–384).

Figure 1 is divided into five (I, II, III, IV, and V) regions. Vectors in each region indicate the forthcoming proliferation of strategies. For instance, in region IV, both  $\alpha$  and  $\beta$  are increasing but  $\gamma$  is decreasing. This means that if water user interaction occurs with any combination of strategies falling in this region, the Grabbers will eventually disappear, as they are outnumbered by Punishers. As a result of the updating process, initially grabbing players opt for sharing or punishing strategies instead. In this particular region the payoff to a punishing or sharing strategy is higher than to the grabbing strategy. We analyse the resulting equilibria and out-of-equilibrium dynamics below, based on historical narratives as summarised in the middle and lower part of table 1.

### 3.3. Introducing private property rights in water

In order to study the effects of water rights privatisation, we modify the unconditional Grabber strategy by introducing a ‘Bourgeois’ strategy. We assume an external authority establishes unquestioned private use rights in water and Bourgeois respect them by claiming the resource when they are the owner (Maynard Smith 1982, 22, Bowles 2004, 85, Bowles and Choi 2013a). They are prepared to fight when contested. As a result, Bourgeois may enter a conflict with Punishers if they own the resource (table 4, table 5). If the other party is the owner, Bourgeois concede the resource. Sharers and Bourgeois share resources equally that are not their property.

The payoffs in tables 3 and table 5 define the stationary strategy combinations: if the entry in the main diagonal is the largest entry in the column, this column presents an ESS (Bowles 2004, 79). The expected payoffs are defined analogously to equations (1)–(3).

## 4. Modelling results

We are now in a position to reconstruct historical water governance episodes in Central Asia through the prism of adaptive agents interacting in an evolutionary game. This exercise provides instructive insights into the incentives and mechanisms that may keep certain governance institutions stable for long time periods or prone to slow or sudden change (see equilibria and dynamics summarised for Central Asia in table 1). Moreover, it can be used to examine the likelihood of success of institutional innovations and their efficiency and distributional implications.

### 4.1. Group sanctioning as a historical baseline equilibrium

In the model community of water users in figure 1, the election-sanctioning mechanism of institutional stability is represented by the left edge of the simplex for which  $\alpha + \beta = 1$ . In a community only consisting of Punishers and Sharers, the water resource is always shared equally and no wasting due to fighting and illicit water appropriation occurs. The result (according to our modelling assumptions in table 3) is egalitarian or ‘Rousseauian’, expressing ‘unconditional sharing and collective upholding of social norms’ as highlighted by the political philosopher Jean-Jacques Rousseau (Bowles 2004, 385).

While the payoffs to Punishers and Sharers are identical all along the left edge of figure 1, the upper portion on the edge above **a** where  $\alpha < \alpha^{\text{max}}$  cannot be invaded by mutant Grabbers (illustrated by the vector set in regions III and IV). Random perturbations may drive the Punisher-Sharer community up and down the edge, but Punishers are in the minority below **a**, so that a potential ‘attack’ of Grabbers can no longer be shielded off. In technical terms, Punisher-Sharer combinations above **a** are ‘neutrally’ stable but

**Table 2.** Actions taken by the row-player when paired with column strategy in the baseline water game.

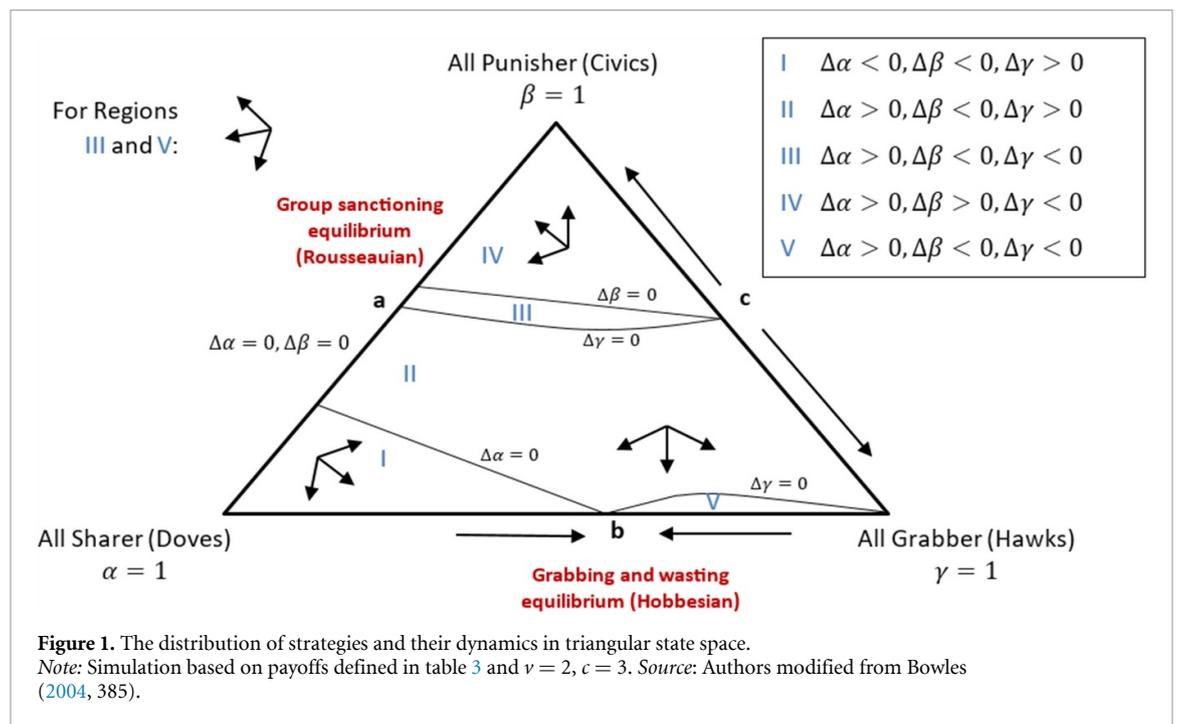
	Grabber	Sharer	Punisher
Grabber	Engages in a fight over a resource worth $v$ , inflicting a cost of $c$ when losing, wins half of the time.	Claims the resource worth $v$ .	Engages in a fight with all Punishers which he wins with probability $(1 - \beta)$ , otherwise bears a cost $c$ .
Sharer	Concedes the resource.	Shares the resource equally.	Shares the resource equally.
Punisher	All Punishers numbering $0 \leq \beta \leq 1$ gather to punish the Grabber. With probability $\beta$ they win and distribute the resource equally among them.	Shares the resource equally.	Shares the resource equally.

Source: Authors modified from Bowles (2004, 383).

**Table 3.** Row-players' payoffs in the baseline water game.

	Grab	Share	Punish
Grab	$(v - c) / 2$	$v$	$(1 - \beta)v - \beta c$
Share	0	$v/2$	$v/2$
Punish	$v/n - (1 - \beta)c$	$v/2$	$v/2$

Source: Authors modified from Bowles (2004, 383).



**Figure 1.** The distribution of strategies and their dynamics in triangular state space.

Note: Simulation based on payoffs defined in table 3 and  $v = 2, c = 3$ . Source: Authors modified from Bowles (2004, 385).

**Table 4.** Actions taken by the row-player when paired with column strategy in the privatisation game.

	Bourgeois	Sharer	Punisher
Bourgeois	If owner, claims the resource, if not concedes it, each with probability 1/2.	If owner, claims the resource, if not share it.	If owner, claims the resource leading to a fight, if not share it.
Sharer	If paired with owner, concedes the resource, if not share equally.	Shares the resource equally.	Shares the resource equally.
Punisher	If paired with owner, all Punishers gather to contest the Bourgeois' claim. Otherwise share equally.	Shares the resource equally.	Shares the resource equally.

Source: Authors modified from Bowles and Choi (2013b, 7).

Table 5. Row-players' payoffs in the privatisation game.

	Bourgeois	Share	Punish
Bourgeois	$v/2$	$3v/4$	$\frac{1}{2}[(1-\beta)v - \beta c] + v/4$
Share	$v/4$	$v/2$	$v/2$
Punish	$\frac{1}{2}[v/n - (1-\beta)c] + v/4$	$v/2$	$v/2$

Source: Authors.

not ESS, as perturbations are not self-correcting and the equilibrium is subject to downward 'drift' along the edge. We argue that this characteristic laid the ground for the historical erosion of group norms in water governance that we study next.

#### 4.2. The erosion of local water governance norms due to central regulation: the 'Kaufman drift'

Our model provides a reconstruction and explanation for the slow deterioration of traditional water governance and its gradual displacement by 'corrupt' water use practices that end up in a stable and long-lasting equilibrium of grabbing and wasting. One way of modelling Russian colonialism in water governance would be by diminishing the ability of local Punishers to prevent water grabbing, e.g. by making it more costly to gather or reduce the effectiveness of punishing. But our model suggests another alternative that does not even require the weakening of the Punishing strategy, which as a cultural mindset may actually have survived colonisation. As soon as chance events shifted the traditional equilibrium composed of Punishers and Sharers below point **a** in figure 1, it becomes subject to further drift into the basin of attraction of the second equilibrium of the model denoted by **b**. (**c** denotes a third equilibrium of Punishers and Grabbers on an unstable saddle that is unlikely to be approached from anywhere in the simplex.) The historical circumstances of colonisation make the drift to **b** more likely, as the degeneration of the sanctioning mechanism will have encouraged grabbing. Moreover, it undermined and ultimately degraded local norms of water sharing. According to the dynamics indicated by the vectors in regions I, II and V of figure 1, this 'Kaufman drift' leads to **b**, an asymptotically stable equilibrium that one may call 'Hobbesian', due to the prevalent grabbing and fighting also described by the English philosopher Thomas Hobbes (Bowles 2004, 385).

Figure 2 displays this drift and highlights an important implication of the ongoing fighting, that is the constantly declining efficiency of the water governance system indicated by the average payoffs on the right edge of the simplex. As figure 1 also illustrates, this inferior equilibrium is an ESS, cannot be invaded by another strategy available in the game, and is therefore likely to persist for a long time.

Historically, it seems likely that Russian colonisers did not *intend* to weaken water governance. The historiographic evidence is ambiguous about the extent

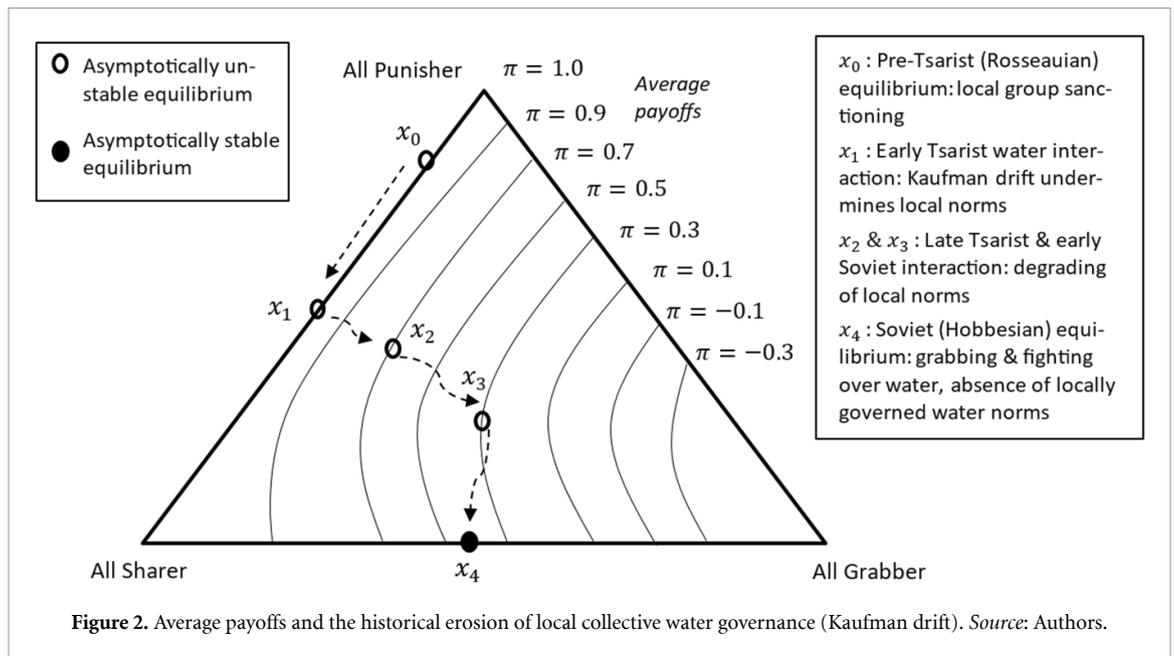
to which the Tsarist authorities maintained a hands-off approach to local water governance or actively imposed regulation (compare Obertreis 2017, 68, 76, with Morrison 2008, 210). Our model is consistent even with this first view, as random perturbations or only slight changes in relative payoffs suffice to tip over the prevailing Rousseauian equilibrium<sup>5</sup>.

#### 4.3. The potential restoration of efficiency through private water rights: the 'Krivoshein game'

In a final step, we theoretically analyse a solution to the inefficiency of grabbing and fighting that has historical, contemporary and systematic relevance: the introduction of private water use rights that may even be tradable. Historical evidence suggests that local custom allowed sale and ownership of irrigation water already under the Khanates, i.e. before Russian colonisation, in the Ferghana valley (Thurman 1999, 68–70). Shortly before the demise of the emperor by the Soviet revolutionaries, in 1905, Tsarist Minister of Agriculture Alexander Vasilyevich Krivoshein drafted a new water law for Central Asia that 'would make it legally possible to buy and sell water, and supersede the mixture of Sharia and custom which had hitherto prevailed' (Morrison 2008, 235). Possibly for ideological reasons, these attempts were not further pursued by the Soviets. Perhaps the problems of administering and enforcing such rights including accurate metering of water portions were then as pertinent as they became after national independence, when international advisors and donors promoted the introduction of IWRM principles to the successor states of the Soviet Union. Treating water as an economic good is a core principle of IWRM (Woodhouse and Muller 2017), a policy framework current Central Asian countries are attempting to implement (Zinzani 2015).

Especially the historical evidence thus raises the question whether private property in water could have emerged 'spontaneously' as part of a mutant strategy invading the traditional Sharer-Punisher or Sharer-Grabber equilibria following tables 4 and 5, with only later attempts at codification by a legal

<sup>5</sup> At  $x_1$  in figure 2, Sharers may be distinguishable from Punishers as they do not engage in punishing any mutant Grabbers, thus evoking 'second order punishment' by the Punishers for free riding on their civic mindedness (Bowles 2004, 387). That water administrators appointed by the colonisers rather than elected by the water users may have abstained from such second order punishment could make all the difference in preventing further drift towards  $x_4$ .



authority. In a systematic perspective on governance mechanisms, tradable private water rights would thus constitute the missing element in the established triplet of community, state, and market provision (Ouchi 1980, Amirova et al 2022).

Under the assumption that water ownership is never in question and that Bourgeois interacting with other types are the owners half of the time, table 5 makes clear that Bourgeois outperforms both Sharers and Punishers as long as the Punishers are a minority (small  $\beta$ ). Once established, it cannot be invaded by either of them, an all-Bourgeois equilibrium is hence an ESS. That is, an established governance system of private water use rights cannot be undermined by collective punishing norms, due to a lack of Punishers. On the other hand, for high levels of  $\beta$  (many Punishers ex-ante), Bourgeois cannot invade a Sharer-Punisher equilibrium. They can only do so once the Punishers are a minority, like in the initial version of the game. An all-Bourgeois equilibrium hence restores a fully efficient and also egalitarian sharing of water benefits, assuming that water rights are in fact distributed equally. By introducing additional information about who is the owner, costly fights are avoided.

What if property rights are contested, or exhibit a degree of ambiguity? In real world settings of developing countries, attaching transparent and enforceable property rights to water may be complicated, for example due to weak enforcement or technical constraints in handling private water rights (Rosegrant and Binswanger 1994)—a situation reminiscent of current-day Central Asia (Petersen et al 2024). Ownership may be ambiguous and Bourgeois may (mistakenly or not) play Grab some of the time even if they are not the owner. How does that affect the likely equilibrium? Somewhat surprisingly, a mutant

Sharer could invade a community of such ‘Contested Bourgeois’. The reason is that Sharers never engage in costly fighting, so they may outperform Contested Bourgeois or Grabbers under some parameter constellations (Bowles 2004, 87)<sup>6</sup>. An all-Bourgeois equilibrium undermined by property rights uncertainty will be shifting to the left on the horizontal edge, approaching the Hobbesian equilibrium of figure 1 and introducing an element of unequal sharing (Bowles and Choi 2013b). We thus end up with the four possible equilibria summarised in table 6.

## 5. Discussion

Here we discuss how our findings relate to the broader discourse on systems resilience in the face of external shocks possibly induced by climate change. These are particularly relevant for Central Asia, where future scenarios suggest altered precipitation regimes, more frequent heat waves and increasing aridity (Reyer et al 2017), or where transboundary water conflicts may severely impact national economies (O’Hara 2000). We also make suggestions for further research.

### 5.1. The role of chance events, external shocks and system resilience

Our study suggests key modelling principles that we argue are quite relevant for other applications in the context of sustainability transformations (see also Bowles 2004, 370–371). The model formalises

<sup>6</sup> Bichsel (2009, 79–85) analyses how a community organisation in the Kyrgyz Ferghana valley drawing on traditional solidarity norms, family ties and the ‘associational power’ yielded by the authority of elders would prevail over communal structures consisting of individual actors that were externally imposed by donor agencies.

**Table 6.** Equilibria depicted by the model.

Equilibrium	Level of expected payoffs (efficiency)	Distribution of sharing outcome	Degree of evolutionary stability
Group sanctioning (Rousseauian)	Maximum	Egalitarian	Neutrally stable, can be dislodged by drift
Grabbing and wasting (Hobbesian)	Severely diminished	Inegalitarian <sup>a</sup>	Asymptotically stable
Contested private water rights	Slightly diminished	Inegalitarian <sup>b</sup>	Asymptotically stable
Uncontested private water rights	Maximum	Egalitarian	Asymptotically stable

Notes: Equilibria correspond to middle section of table 1.

<sup>a</sup> referring to interactions between Grabbers and Sharers.

<sup>b</sup> referring to interactions between Contested Bourgeois and Sharers. In equilibrium, expected payoffs across all interactions are identical for the involved strategies.

Source: Authors.

how initial conditions matter and how historical path dependencies determine the governance options today. We demonstrate that chance events and local experimentation play an important role in institutional change and can have large, unintended consequences stemming from punctuated equilibria. The erosion of traditional norms of water allocation through the central appointment of administrators is our key illustration for Central Asia (section 4.2). On the other hand, the model shows how wasteful institutions may persist for a long time and may be hard to dislodge, such as an asymptotically stable equilibrium of grabbing and wasting water. The model allows for collective action enforcing governance rules that stabilise the sustainable use of natural resources. We therefore suggest that institutions and behavioural strategies co-evolve and should be analysed in conjunction.

If resilience is the capacity over time of agents to avoid extreme economic distress in the face of various stressors (Barrett and Conostas 2014, 14 626), the evolutionary stable equilibria with maximum payoffs in table 6 indicate the normative reference points for system resilience in our model. Reyer *et al* (2017, 1644) summarise evidence suggesting that, in the future, more frequent heat extremes or reduced water availability may dwarf agricultural productivity in irrigated areas of Central Asia by up to 50%. Similarly, border conflicts over water may depress agricultural yields in Central Asia (Bichsel 2009). In our model, the overall level of  $\pi$  in figure 2 will thus decrease, shifting the set of iso-profit contours to the left. If we assume there exists a subsistence constraint  $\pi^{\min}$  below which agents cannot survive (e.g. a minimum income generated from farming activities), such a shock will lead to the extinction of low payoff equilibria and hence disruptive change.

However, in the model, external shocks need not only be negative for systems resilience. Chance events

emerging from increasing uncertainty, external shocks or disasters may also increase idiosyncratic play that makes it more likely to dislodge an equilibrium. Shocks may help navigating a community from ‘good’ to ‘bad’ equilibria and vice versa. They may also spur the invention of new or revitalise ‘traditional’ strategies (such as the case mentioned in footnote 3).

Future research on the interaction between water use strategies, institutions and technology appears especially promising. On the one hand, technological lock-ins of large-scale irrigation infrastructure (the ‘water machine’, Djanibekov *et al* 2013) curtailed water reform opportunities in Central Asia. On the other hand, certain technologies (e.g. digital tools of water monitoring or decentralised water reservoirs, Parra-López *et al* 2025) could enhance the payoffs for either group sanctioning mechanisms or private use rights, creating technical-institutional synergies (Bowles and Choi 2019, 2190).

## 5.2. The analytical potential of out-of-equilibrium dynamics

The erosion of water governance norms and the contested water rights analysed above illustrate how this modelling approach can tackle decaying or incompletely implemented governance modes. Once water norms have drifted away from the punishing equilibrium, they can be undermined, as during Russian and Soviet colonisation. If actors deviate from ideal-type Bourgeois play sometimes, the full potential of private property rights is diminished, a situation quite consistent with contemporary water arrangements in Central Asia (Petersen *et al* 2024, 9).

These insights can motivate new research questions to be further investigated empirically, such as the following: Was the drift to grabbing and wasting during Russian conquest due to community members’ fading ability to punish or the deliberate switch

to grabbing as the preferred strategy? To what extent did colonisers intend to weaken community water governance or had to accept it as an unintended consequence of their centralisation approach? Did the absence of second-order punishment of Sharers by Punishers under Soviet colonisation contribute to the emergence of Grabbers? Does the same mechanism prevent the successful establishment of water user associations after independence, such as by donor agencies not taking into account traditional authorities (Bichsel 2009, 68–85)?

### 5.3. Implications for the current Central Asian water reform agenda

Researchers have recommended that Central Asian water administrators should reconsider pre-Tsarist community principles of water governance, even if they disappeared in actual practice (e.g. O'Hara 2000, Amirova *et al* 2019). Yet there have been few real changes in the Central Asian governance of irrigation water thirty years after the Soviet Union. Techno-centric visions of water governance persist, an unlearning of water wasting practices did not take place and lacking civil society engagement and low levels of trust prevent experimentation (Herrfahrdt-Pähle *et al* 2020). Long-standing path dependencies in water governance extend into the post-Soviet period (Sehring 2009), and the current discourse is about water management, not water governance (Sehring 2020). Our analysis of self-reinforcing, inefficient 'grabbing' equilibria provides specific explanations why beneficial change has been so rare. Through recourse to community norms or private use rights, we show which levers could promote alternative water governance in the future, with which consequences for efficiency and distribution.

Even so, in the course of political liberalisation after the passing of former president Islam Karimov in 2016, the Uzbek government suggested a new Concept for Water Sector Development for 2020–2030. The document highlights the introduction of market principles for water pricing and the allocation of public funds. It stresses the decentralisation of water management by transferring state-owned inter-farm infrastructure to private organisations, voluntary unions of water users and clusters, and inviting private and foreign investors into the water sector. According to the proposal, the guiding principles of these changes should be transparency, economic efficiency, social justice and environmental sustainability. The shift to private recovery of water infrastructure costs, especially those serving agriculture, will imply the introduction of volumetric pricing of delivered water. Furthermore, the introduction of a water market will permit the transferability of water rights among agricultural producers based on monetary compensation. These are the preconditions for yielding the benefits of private water use rights as discussed in section 4.3. Similarly, the Tajik government

suggested speeding up the adoption of IWRM principles, including a more active participation of water users and civil society in the water decentralisation process (Amirova *et al* 2022), thus enabling a group sanctioning approach as investigated in section 4.1.

## 6. Conclusions

Our evolutionary model of community-based water governance provides insights into how traditional water allocation norms were dismantled by Russian colonisers and Soviet bureaucrats, and how current policymakers could learn from these historical experiences for establishing more resilient institutions of water governance. Of course relatively simple models like ours do not claim to deliver an empirically accurate account of water governance in Central Asia or elsewhere. The model provides a heuristic, offering plausible narratives with hints where to look for causal mechanisms and relevant system interlinkages. Important drivers such as climate change or the political economy of transboundary water allocation remain external to the model. But our results do suggest a focus on local interaction as an arena of institutional change and they make a renewed plea for the benefits of uncontested property rights as an institutional solution to water governance. While Kaufman-style interventions will crowd out rather than crowd in the interaction mechanisms shown to be beneficial in our model, there is a role for government in creating room for decentralised policy initiatives such as IWRM. They have the potential to harness institutional complementarities that even make use of both community and market mechanisms for water governance.

### Data availability statement

No new data were created or analysed in this study.

### Acknowledgment

This study draws on a chapter of the first author's dissertation thesis conducted in the framework of the 'Institutional change in land and labour relations of Central Asia's irrigated agriculture' (AGRICCHANGE) project funded by the VolkswagenStiftung (Grant No. 89821). We gratefully acknowledge this financial support. A post-doctoral fellowship project, 'Institutions, change mechanisms and impacts in natural resource management of Central Asia' (INRESCA), funded by VolkswagenStiftung (Grant No. 96802), supported Iroda Amirova's follow-up work on this paper. Martin Petrick's work on the manuscript was supported by the German Academic Exchange Service (DAAD) from funds of the Federal Ministry for Economic Cooperation (BMZ), SDGnexus Network (Grant No. 57753302), program 'exceed 2025-2029—Hochschulexzellenz in der

Entwicklungszusammenarbeit'. Nodir Djanibekov's work on this manuscript was supported by the project 'Navigating shocks and transformations in rural communities: An evolutionary resilience perspective from Central Asia (CARE)' funded by VolkswagenStiftung (Grant 9E149).

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## References

- Abdullaev I and Rakhmatullaev S 2015 Transformation of water management in Central Asia: from State-centric, hydraulic mission to socio-political control *Environ. Earth Sci.* **73** 849–61
- Acemoglu D and Robinson J A 2012 *Why Nations Fail: The Origins of Power, Prosperity and Poverty* (Profile Books)
- Amirova I, Petrick M and Djanibekov N 2019 Long- and short-term determinants of water user cooperation: experimental evidence from Central Asia *World Dev.* **113** 10–25
- Amirova I, Petrick M and Djanibekov N 2022 *Community, State and Market: Understanding Historical Water Governance Evolution in Central Asia (IAMO Discussion Paper vol 200)* (IAMO)
- Barrett C B and Constan M A 2014 Toward a theory of resilience for international development applications *Proc. Natl Acad. Sci. USA* **111** 14625–30
- Bichsel C 2009 *Conflict Transformation in Central Asia: Irrigation Disputes in the Ferghana Valley (Central Asian Studies Series vol 14)* (Routledge)
- Bowles S 2004 *Microeconomics: Behavior, Institutions, and Evolution (The Roundtable Series in Behavioral Economics)* (Russell Sage Foundation)
- Bowles S and Choi J-K 2013a Coevolution of farming and private property during the early Holocene *Proc. Natl Acad. Sci. USA* **110** 8830–5
- Bowles S and Choi J-K 2013b Supplementary information for 'The coevolution of farming and private property during the early Holocene' *Proc. Natl Acad. Sci. USA* **110** 1–29
- Bowles S and Choi J-K 2019 The Neolithic agricultural revolution and the origins of private property *J. Political Econ.* **127** 2186–228
- Brick Murtazashvili J 2022 Customary governance and the state in Central Eurasia *Central Asia: Contexts for Understanding ed D W Montgomery* (University of Pittsburgh Press) pp 599–605
- Dadabaev T 2017 Between state and society: the position of the Mahalla in Uzbekistan *Social Capital Construction and Governance in Central Asia (Politics and History in Central Asia)* ed T Dadabaev et al (Palgrave Macmillan) pp 77–95
- Djanibekov U, van Assche K, Boezeman D and Djanibekov N 2013 Understanding contracts in evolving agro-economies: Farmers, dekhqans and networks in Khorezm, Uzbekistan *J. Rural Stud.* **32** 137–47
- Gorshenina S 2021 Orientalism, postcolonial and decolonial frames on Central Asia: theoretical relevance and applicability *European Handbook of Central Asian Studies: History, Politics, and Societies* ed J J van den Bosch et al (ibidem) pp 177–241
- Herrfahrdt-Pähle E, Schlüter M, Olsson P, Folke C, Gelcich S and Pahl-Wostl C 2020 Sustainability transformations: socio-political shocks as opportunities for governance transitions *Glob. Environ. Change* **63** 102097
- Lerman Z, Garcia-Garcia J and Wichelns D 1996 Land and Water Policies in Uzbekistan *Post-Sov. Geogr. Econ.* **37** 145–74
- Maynard Smith J 1982 *Evolution and the Theory of Games* (Cambridge University Press)
- Micklin P P 1988 Desiccation of the Aral Sea: a water management disaster in the Soviet Union *Science* **241** 1170–6
- Morrison A S 2008 *Russian Rule in Samarkand 1868–1910: A Comparison with British India (Oxford Historical Monographs)* (Oxford University Press)
- O'Hara S L 2000 Lessons from the past: water management in Central Asia *Water Policy* **2** 365–84
- Obertreis J 2017 Imperial Desert Dreams: cotton growing and irrigation in Central Asia 1860–1991 (*Kultur- und Sozialgeschichte Osteuropas* vol 8 (V&R unipress))
- Ouchi W G 1980 Markets, Bureaucracies, and Clans *Adm. Sci. Q.* **25** 129–41
- Parra-López C, Ben Abdallah S, Garcia-Garcia G, Hassoun A, Trollman H, Jagtap S, Gupta S, Ait-Kaddour A, Makmuang S and Carmona-Torres C 2025 Digital technologies for water use and management in agriculture: recent applications and future outlook *Agric. Water Manage.* **309** 109347
- Petersen G, Madumarov E, Uteyeva A, Gaforzoda B, Mergenova G and Karimov A 2024 *Water Sector Financial Governance Gap Analysis in Central Asia* (CAREC Institute)
- Peterson M K 2019 *Pipe Dreams: Water and Empire in Central Asia's Aral Sea Basin (Studies in Environment and History)* (Cambridge University Press)
- Reyer C P et al 2017 Climate change impacts in Central Asia and their implications for development *Reg. Environ. Change* **17** 1639–50
- Rosegrant M W and Binswanger H P 1994 Markets in tradable water rights: potential for efficiency gains in developing country water resource allocation *World Dev.* **22** 1613–25
- Schlüter M et al 2017 A framework for mapping and comparing behavioural theories in models of social-ecological systems *Ecol. Econ.* **131** 21–35
- Sehring J 2009 Path dependencies and institutional bricolage in post-Soviet water governance *Water Altern.* **2** 61–81
- Sehring J 2020 Unequal distribution: academic knowledge production on water governance in Central Asia *Water Security* **9** 100057

- Spoor M 1998 The Aral Sea basin crisis: transition and environment in former soviet Central Asia *Dev. Change* **29** 409–35
- Thurman J M 1999 Modes of Organization in Central Asian Irrigation: the Ferghana Valley, 1876 to present PhD dissertation Indiana University Bloomington
- Veldwisch G J A and Mollinga P P 2013 Lost in transition? The introduction of water users associations in Uzbekistan *Water Int.* **38** 758–73
- Woodhouse P and Muller M 2017 Water governance—an historical perspective on current debates *World Dev.* **92** 225–41
- Xenarios S, Schmidt-Vogt D, Qadir M, Janusz-Pawletta B and Abdullaev I (eds) 2020 *The Aral Sea Basin: Water for Sustainable Development in Central Asia (Earthscan Series on Major River Basins of the World)* (Routledge)
- Zinzani A 2015 *The Logics of Water Policies in Central Asia: The IWRM Implementation in Uzbekistan and Kazakhstan* vol 23 (LIT) Geographie