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Unlocking aquifer sustainability through irrigator-driven groundwater conservation

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Aquifer depletion due to intensive irrigation threatens global economies, food security and ecosystems. This Perspective examines the hydrological, social and economic complexities of managing groundwater resources, focusing on the Sheridan 6 Local Enhanced Management Area in the US High Plains aquifer. Here irrigator-led conservation efforts reduced groundwater use by 25% and slowed aquifer depletion by 65% while maintaining farmers' incomes. This success resulted from a hybrid integration of bottom-up rule development with top-down enforcement, providing flexible multi-year water allocations and aligning management with local conditions. From this, we identify transferable governance tenets for sustainable groundwater management in similar regions.

Over the past century, large-scale groundwater use has substantially altered hydrological and human systems. Groundwater accounts for approximately 30% of global freshwater use and supports about 40% of irrigation worldwide[1,2]. Moreover, the demand for agricultural water is expected to rise due to compound stresses, including climate-induced water scarcity, population growth and shifts in dietary patterns[3]. This heavy reliance has led to widespread aquifer depletion as users extract groundwater faster than it can be replenished[4]. Such depletion poses a serious threat to water and food supplies, affecting the livelihoods of over 1.5 billion people, 17% of global crop production and 13% of the world's gross domestic product[2,5]. The environmental repercussions are equally concerning, including drying of formerly perennial rivers and streams, sea-level rise, saltwater intrusion and land subsidence[6].

Aquifer depletion is a 'wicked' problem with no simple solution. It involves multiple users and decision-makers with conflicting goals, governance across multiple jurisdictions and scales, and decisions hampered by uncertainties from limited data and knowledge[7]. Groundwater use is often treated as a zero-sum game, where irrigators pump what they can for short-term gain with few incentives for individual conservation of this common-pool resource. Globally, aquifer depletion occurs under diverse climatic, hydrological, legal, social and economic conditions, preventing a uniform solution[2,8,9]. Although reducing pumping is imperative to slow or halt depletion, achieving this is challenging due to the complex web of social and economic factors related to irrigation[10]. Despite the development of many technical solutions to reduce groundwater use, the key to success lies in establishing appropriate institutional frameworks[11]. For example, improvements in irrigation efficiency typically fail to reduce groundwater use because farmers tend to use the saved water to increase irrigated acreage or shift to more water-intensive crops[12] unless they are tied to a binding agreement to reduce water use[10]. This illustrates the need to anticipate unintended consequences when formulating policies and institutions for groundwater management.

Groundwater conservation demands robust governance systems with clear objectives, tenets and rules, where transparency and information are crucial for fostering collective action[13]. Two management

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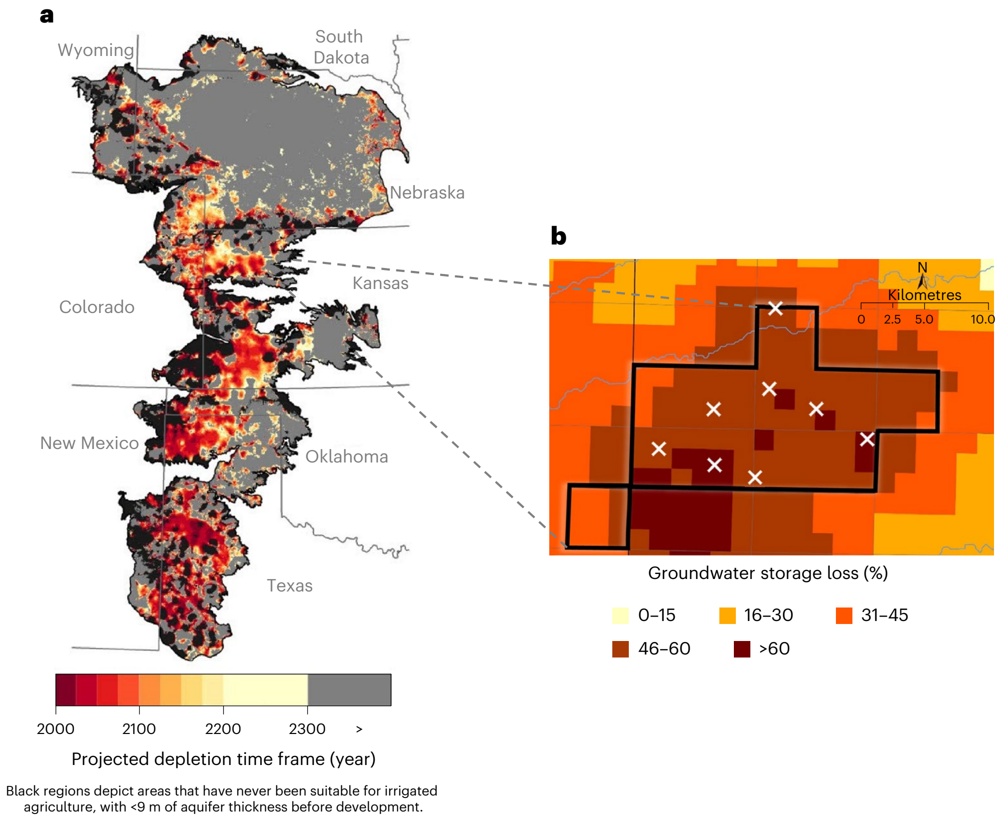

Fig. 1 | Depletion in the High Plains aquifer and study area. a, Projected depletion timeline of the High Plains aquifer until large-scale irrigation becomes impractical based on extrapolation of current trends[58,59]. **b**, Percentage loss of groundwater storage from predevelopment to the average for 2021–2023 within the SD-6 LEMA (depicted by the black polygon) in Northwest Kansas[26] and the wells (depicted as white Xs) used to monitor groundwater levels[27].

approaches are often employed: bottom-up, which involves local water users self-organizing and creating rules suited to their conditions, and top-down, which involves implementing rules defined at higher governance levels. Top-down approaches often fail to translate plans into effective conservation actions as they neglect the highly heterogeneous conditions characterizing large common-pool resources and often lack adaptability for technological advancements and consequences[14]. Moreover, governmental interventions in groundwater use are frequently met with resistance from irrigators, who see such measures as limiting their autonomy over farm management[15]. Bottom-up approaches, such as irrigator-led groundwater conservation programmes, leverage local knowledge and relationships to establish governance systems that can achieve desired outcomes, such as slowing aquifer depletion[16]. Although small rural communities have found success with community-based groundwater management, this success is not easily transferable to large-scale aquifer management because more diverse social and environmental conditions challenge the effectiveness of broad rulemaking.

Navigating technical and social complexities in groundwater management requires a holistic perspective that includes the understanding of hydrological processes with the root economic, legal and social causes of pumping[17]. This approach requires collaboration between groundwater users and governments, or 'comanagement'[17] in which responsibilities in resource management are shared across scales and organizations. Successful comanagement thus depends on understanding complex sociopolitical dynamics. Learning from examples of self-governance and comanagement is critical for identifying pathways to aquifer sustainability. Recent case studies in France, Spain and the United States highlighted the roles of governments in regulating water use and enforcing pumping caps, and the roles of users in innovating to reduce groundwater use[18].

In this Perspective, we present the Sheridan 6 Local Enhanced Management Area (SD-6 LEMA) in a heavily depleted portion of the US High Plains aquifer as a successful comanaged model for groundwater conservation. From our experience, we identify emergent tenets that may be transferable to other regions within heavily pumped aquifers. Insights from the SD-6 LEMA's first decade reveal several key factors for successful conservation plans: (1) the hybrid integration of bottom-up rule development with top-down enforcement, (2) flexibility attained through a multi-year cap on irrigation and (3) focusing on areas of relatively homogeneous environmental and social conditions. These lead us to propose governance tenets for sustainable aquifer management that incorporate social, hydrological and economic factors to address the vexing problem of aquifer depletion.

Irrigator-led water conservation in Kansas

The High Plains aquifer in the central United States, stretching from South Dakota to Texas, supports a US$35 billion agriculture industry[19]. Decades of intensive pumping for irrigation have caused notable water-level declines across much of its extent (Fig. 1a), leading to a growing recognition of the need for collective conservation measures to preserve this vital resource. This is particularly true in the portion of the aquifer in the state of Kansas. In 2012, the Kansas Legislature enacted the Local Enhanced Management Area (LEMA) programme, which empowers local groundwater management districts (GMDs) to create enforceable plans subject to approval by the chief engineer of the Division of Water Resources within the Kansas Department of Agriculture (KDA-DWR)[20,21].

The SD-6 LEMA was initially approved for a 5 year period beginning in 2013 as the first conservation plan developed under the LEMA statute. The area encompasses 255 km^2 (99 mi^2) in Northwest Kansas, an area heavily reliant on groundwater irrigation with scant surface-water

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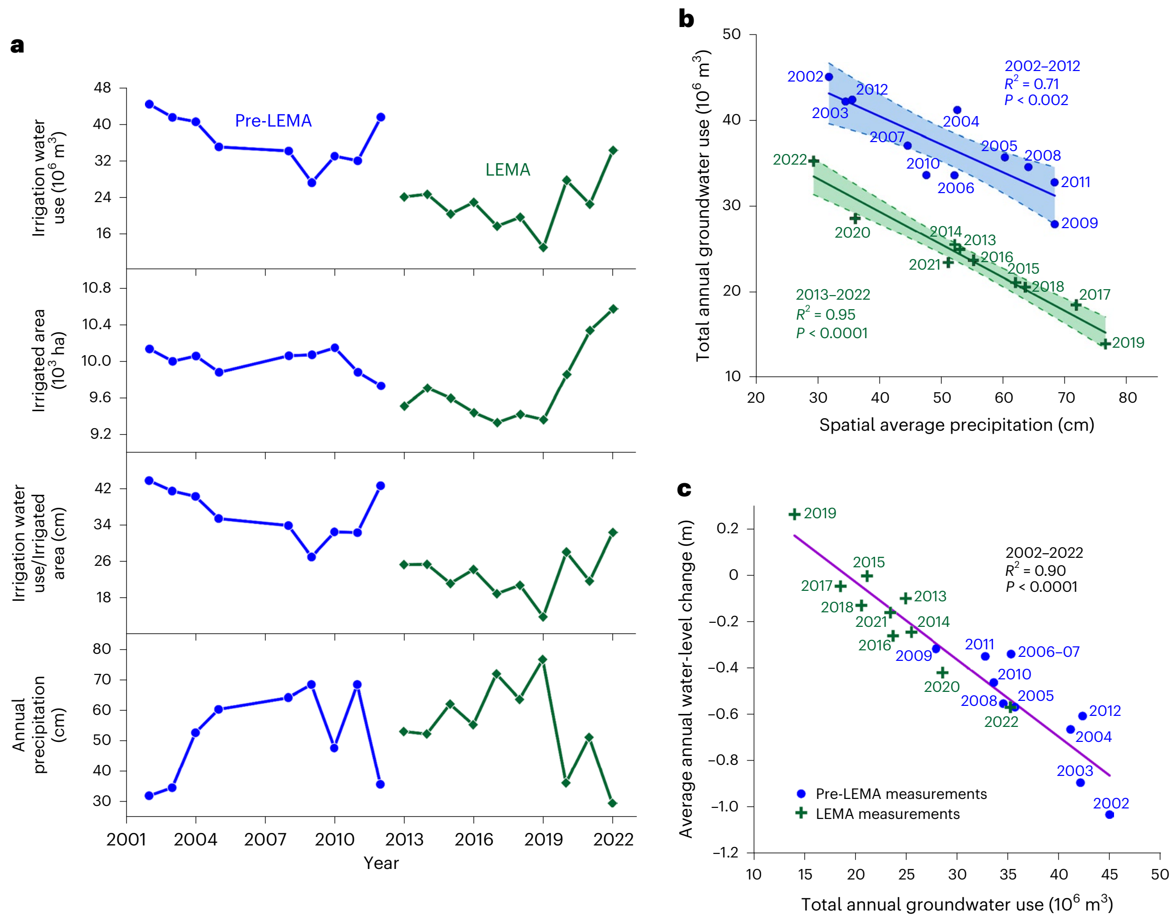


Fig. 2 | Hydrological impacts of the SD-6 LEMA. a, Hydrological and agronomic conditions are compared before (blue) and during (green) the first decade of the SD-6 LEMA. **b**, Shifting pumping response, showing reduced total annual groundwater use for similar precipitation levels after the start of the SD-6 LEMA. The shaded 95% level confidence intervals are bounded by dashed lines. **c**, Slowing annual water-level decline rates due to reductions in groundwater use after the start of the SD-6 LEMA. The solid line represents the best fit for the data[4,24].

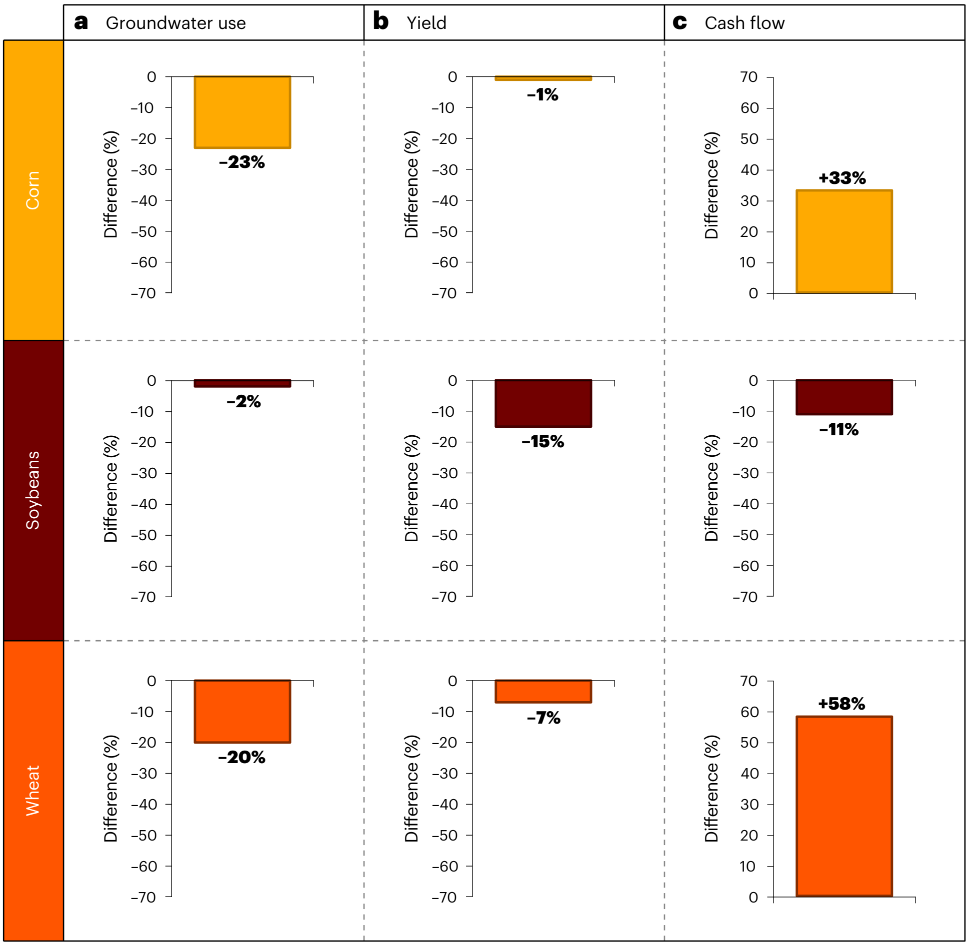
resources and limited recharge capacity[22,23], and was prioritized due to sizable water-level declines—up to ~9 m (~30 ft) since 1980, representing >45% of available groundwater[24] (Fig. 1b). Developed collaboratively by local irrigators in partnership with the Northwest Kansas Groundwater Management District #4 (GMD4), in which the SD-6 LEMA resides, the primary objective of the SD-6 LEMA is to ensure a sustainable water supply for future generations[17]. Under the SD-6 LEMA, irrigators committed to a 5 year water allocation of 140 cm depth of irrigated water applied per hectare (55 inches per acre), on the basis of the maximum area irrigated annually between 2007 and 2010[25]. This allocation is an approximately 20% reduction compared with the regional historical annual average withdrawals (~36 cm per hectare annually (14 inches per acre) for the 2002–2012 period)[26]. The SD-6 LEMA's reduction targets were developed on the basis of historic water use (Fig. 2a), which was known because irrigation water use in Kansas is required to be monitored using a totalizing flowmeter and reported annually to the KDA-DWR; non-compliance with these regulations results in stringent penalties[27].

Hydrological, economic, and social impacts

Irrigators in the SD-6 LEMA exceeded their initial 20% water-use reduction target[4,23,28–31], leading to an ~65% decrease in depletion rate within the LEMA, from an average 42.7 cm (1.4 ft) per year in 2002–2012 to an average 18.3 cm (0.6 ft) per year in 2013–2022 (Fig. 2c)[4,10]. Water use under similar climatic conditions was ~25% lower during the LEMA period (2013–2022) compared with the pre-LEMA period (2002–2012), and the relationship between water use and precipitation has remained consistent throughout the LEMA period[23] (Fig. 2b). Groundwater-use reductions, measured by decreasing irrigation depths, were attained primarily through enhancements in irrigation efficiency, which accounted for 72% of the total reductions (Fig. 2a)[28]. This underscores a crucial element in effective conservation efforts—combining legally enforceable reductions in overall water use with the flexibility to improve the on-field irrigation efficiency[10].

The sharp decrease in water use at the start of the LEMA in 2013 can be attributed primarily to groundwater conservation with a secondary effect from wetter conditions in 2013 compared with 2012 (Fig. 2a). Around 90% of the reduction in water use was attributed to decreased corn irrigation, as ~70% of the irrigated area in the SD-6 LEMA was planted to corn[28]. Methods to enhance irrigation efficiency included reducing seed density to sustain fully irrigated crops amid water scarcity conditions and adopting new irrigation management technologies, particularly irrigation scheduling and soil moisture monitoring[28]. These advancements enable more-efficient deficit irrigation practices by tailoring water and fertilizer applications according to each crop's needs, thereby minimizing water loss and increasing profitability.

Additional water-use reductions stemmed from switching to crops with lower irrigation demands (19%), such as sorghum and wheat, and scaling back on irrigated acreage (9%) in the first 7 years[28]. Notably, there has been a recent uptick in irrigated areas (Fig. 2a), which is probably due to the irrigators having banked enough water for greater use at the end of the 5 year period. Our assessment is that farmers met the water-use reductions through improvements in irrigation efficiency and crop selection, emphasizing the adaptive capacity fostered by the



Control area was a 3.22-km-wide area around the SD-6 LEMA in the High Plains aquifer. Within this control area, there was the following number of producer-reported observations:

	Corn	Soybeans	Wheat
SD-6 LEMA	20	5	5
Control area	11	4	3

Fig. 3 | Economic benefits from SD-6 LEMA's groundwater-use reduction. **a**–**c**, Relative effect (%) of the SD-6 LEMA in the first 5-year period in groundwater use in terms of applied irrigation depth per irrigated hectare (**a**), crop yield (**b**) and cash flows (**c**) for corn, soybeans and wheat. Sample sizes are shown in the table at the bottom. Cash flow is defined as gross revenue (crop price × crop yield) minus variable production costs (fertilizer, seed, herbicide, hired labour, pumping costs and so on.)[30].

SD-6 LEMA even in cases of drought (for example, 2022). These diverse adaptations emphasize the importance of setting clear groundwater conservation targets while allowing for flexibility in how those targets are met[28].

Several social and political factors have facilitated these adaptations and enabled the important reduction in water use within the SD-6 LEMA. Most important, there has been a shift in irrigator mindsets. Irrigators are increasingly prioritizing net income and water productivity over maximizing crop yield, the norm in the past[32]. This shift can be attributed to their ability to maintain profitability despite substantial reductions in water use. Their adaptability has enabled them to avoid substantial yield and economic losses that might have arisen from transitioning to non-irrigated production, a scenario that could have unfolded if depletion had continued at historical rates[29,33].

Evidence from the initial 5 year period of the SD-6 LEMA shows that, despite lower crop yields (Fig. 3b) due to reduced irrigation depths (Fig. 3a), adoption of less-water-intensive crops and, most important, decreased energy expenses from groundwater pumping helped irrigators sustain their cash flows[30] (Fig. 3c). Since both the LEMA and control regions are within similar markets, changes in crop prices over time do not affect the results of Fig. 3, although decreased energy expenses are most likely to offset yield reductions when crop prices are low and/or energy costs are high. An examination of farm-level responses to an agricultural census supports this observation, revealing a notable 45% decrease in total expenditures, particularly in energy, fertilizer and chemical costs[34]. The 33% increase in cash flow reported by corn producers within the LEMA, despite an ~1% decrease in corn yield compared with their non-LEMA neighbours, showcases the resilience and adaptability of agricultural methods under water-use limitations[30]. This adaptability is further evidenced by shifts in crop selection, with an ~13% reduction in irrigated corn acreage accompanied by increases in less-water-demanding crops such as sorghum and wheat. Corn irrigation management also saw improvements, with an ~23% reduction in groundwater use per irrigated hectare. Although other crops such as sorghum were associated with lower water use, expanded irrigated area and more-efficient irrigation within the SD-6 LEMA, these crops have a smaller sample size than corn[30], so the representativeness of their results is more uncertain.

The SD-6 LEMA yielded an estimated increase in cash flow of US$2.24 million over the initial five-year period compared with

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a business-as-usual scenario[35]. While gross revenue decreased by US$0.60 million due to lower crop yields and changes in crops, energy expenses decreased by US$2.85 million, resulting in a net increase in cash flow since energy expenses typically account for nearly 10% of corn cultivation costs in western Kansas[12]. These economic gains are in stark contrast with projections indicating substantial losses (estimated $34 million annually for Kansas) if the current depletion trajectory persists until 2050[36]. These benefits reveal the critical significance of proactive and adaptable water management strategies for sustaining both economic viability and agricultural productivity.

The notable reduction in the rate of aquifer decline stands as clear evidence of the SD-6 LEMA's positive impact on the hydrological system, while continued farmer support, changes in social norms and sustained farm profits demonstrate the positive economic and social aspects. Yet despite the evident benefits and farmers voting to renew the programme for two additional 5 year periods (2018–2022 and 2023–2027), concerns have arisen that the LEMA was renewed with no further reductions in pumping allocations[25]. Although the programme has slowed groundwater declines, it has not achieved sustainable extraction levels, as illustrated by ongoing declines albeit at a moderated pace (Fig. 2c). Studies indicate that the effectiveness of groundwater conservation measures over the long term hinges on the equilibration of the aquifer water balance to conditions of reduced irrigation. Following the reduction in pumping, recharge to the aquifer and/or lateral inflows into the SD-6 LEMA area are likely to eventually decline. Consequently, it is anticipated that the rate of aquifer decline will eventually increase as the hydrological system responds to pumping reductions, although the decline rate will still be an improvement over pre-LEMA conditions[20,37]. Ultimately, the approximately 25% decrease in pumping within the SD-6 LEMA could extend the aquifer's median usable lifespan by 25–35 years, although uncertainty about that range is high[20,37].

A survey among irrigators in GMD4 revealed a consensus favouring stricter pumping restrictions while expressing a need for greater flexibility in meeting these restrictions, especially if aquifer depletion worsens within the GMD[8]. This shift in mindset shows the influence of the SD-6 LEMA within the broader framework of local groundwater management[38]. Many irrigators in neighbouring areas regard the SD-6 LEMA as an effective example of groundwater conservation. Attempts to replicate its success elsewhere in west-central and northwestern Kansas[39], however, have yielded mixed outcomes (Table 1), with statistically significant reductions in water use observed in only one other LEMA[23].

Table 1 | Chronological overview of the establishment of the SD-6 LEMA and consequent LEMAs established in western Kansas

Year	Policy Event
1945	Kansas adopts the prior appropriation doctrine statewide, applying the 'first in time, first in right' principle to groundwater.
1957	Kansas relaxes the legal standard for approving new water rights, thereby enabling the over-appropriation of groundwater resources.
1972	Kansas enacts the Groundwater Management District Act, giving local districts a role in water rights management.
2008–2011	Irrigators in Sheridan and Thomas counties (area known as SD-6) develop locally designed and legally binding pumping-reduction plans to promote aquifer and economic sustainability.
2012	Kansas enacts K.S.A. 82a-1041, providing for LEMAs. Using Kansas Geological Survey and KDA-DWR analyses, and after 11 public hearings, the GMD4 submits its proposed LEMA programme for SD-6 to the chief engineer of KDA-DWR.
2013	KDA-DWR approves the SD-6 LEMA, which reduces most authorized groundwater pumping allocations in SD-6 by 20% for 5 years.
2018	On the basis of the success of the first 5 years, GMD4 submits a proposal to renew the SD-6 LEMA for another 5 years (2018–2022); KDA-DWR approves the renewal. GMD4 implements a district-wide LEM for an initial 5 year period, recently extended until 2027. However, data indicate no statistically significant shift in the district's irrigation water consumption to date[23,24].
2021	GMD1 (to the south of GMD4) implements a LEMA in Wichita County, Kansas, leading to estimated irrigation reductions of 39.5%[24].
2022	GMD4 submits and KDA-DWR approves renewal of the SD-6 LEMA for another 5 years (2023–2027).
2023	GMD1 implements a second LEMA encompassing the district's four other counties.

Key factors enabling success

Irrigator-driven groundwater comanagement presents a promising approach to address aquifer depletion. However, collective action alone does not guarantee success. Examining comanagement in the SD-6 LEMA can help pinpoint factors contributing to effective management and the barriers hindering sustainable solutions[13]. Previous studies have identified several factors that played a role in the success of the SD-6 LEMA. These include widespread awareness of substantial declines in the area's water table and the economic ramifications of such declines, legislative support for LEMA initiatives, visionary leadership, a limited number of water-right holders, a preference for local governance, confidence in consent-based processes and the potential imposition of more-severe top-down restrictions. We highlight three key aspects as particularly worthy of replication in other contexts: (1) the integration of bottom-up rule development with top-down enforcement, (2) multi-year flexibility in water allocations to meet reduced irrigation targets and (3) aligning management area boundaries with relatively homogeneous environmental and social conditions.

Top-down and bottom-up hybrid model

Water rights in the United States are governed by legal frameworks that vary from state to state. These include the prior appropriation doctrine, which protects senior water rights in times of shortage; the reasonable use doctrine, which permits landowners to use water without constraints as long as it benefits the overlying land; the correlative rights doctrine, which requires equitable sharing of water resources within an aquifer among landowners; and the absolute ownership doctrine, which confers exclusive ownership of water beneath a landowner's property[40]. Recognizing the challenges of groundwater management, many states are treating groundwater as a nonrenewable resource. Consequently, some regions allowed water withdrawals on the basis of a calculated depletion formula rather than focusing on aquifer sustainability[40,41]. In late 2022, the state of Kansas, recognizing the aquifer depletion's long-term economic impacts, decided that the policy of planned depletion was no longer in the state's best interest[10].

The inception of the LEMA statute arose from widespread concerns regarding the ineffectiveness of prevailing water management tools, including existing voluntary conservation options, to curb aquifer depletion. By actively engaging local irrigators and instilling within them the confidence to design the management of local groundwater resources, the LEMA statute fostered an approach that circumvented challenges associated with top-down approaches[42]. Specifically, a consortium of irrigators collectively committed to groundwater preservation and collaboratively devised a comprehensive strategy that uniformly affected all water rights (Table 1)[25]. On approval, water rights owners within the SD-6 region became obligated to participate. While imposing constraints on groundwater use, the SD-6 LEMA allows junior rights holders—those with a lower priority to access limited groundwater—to continue accessing groundwater. Unlike the 'prior appropriation' provision of the Kansas Water Appropriation Act, which curbs

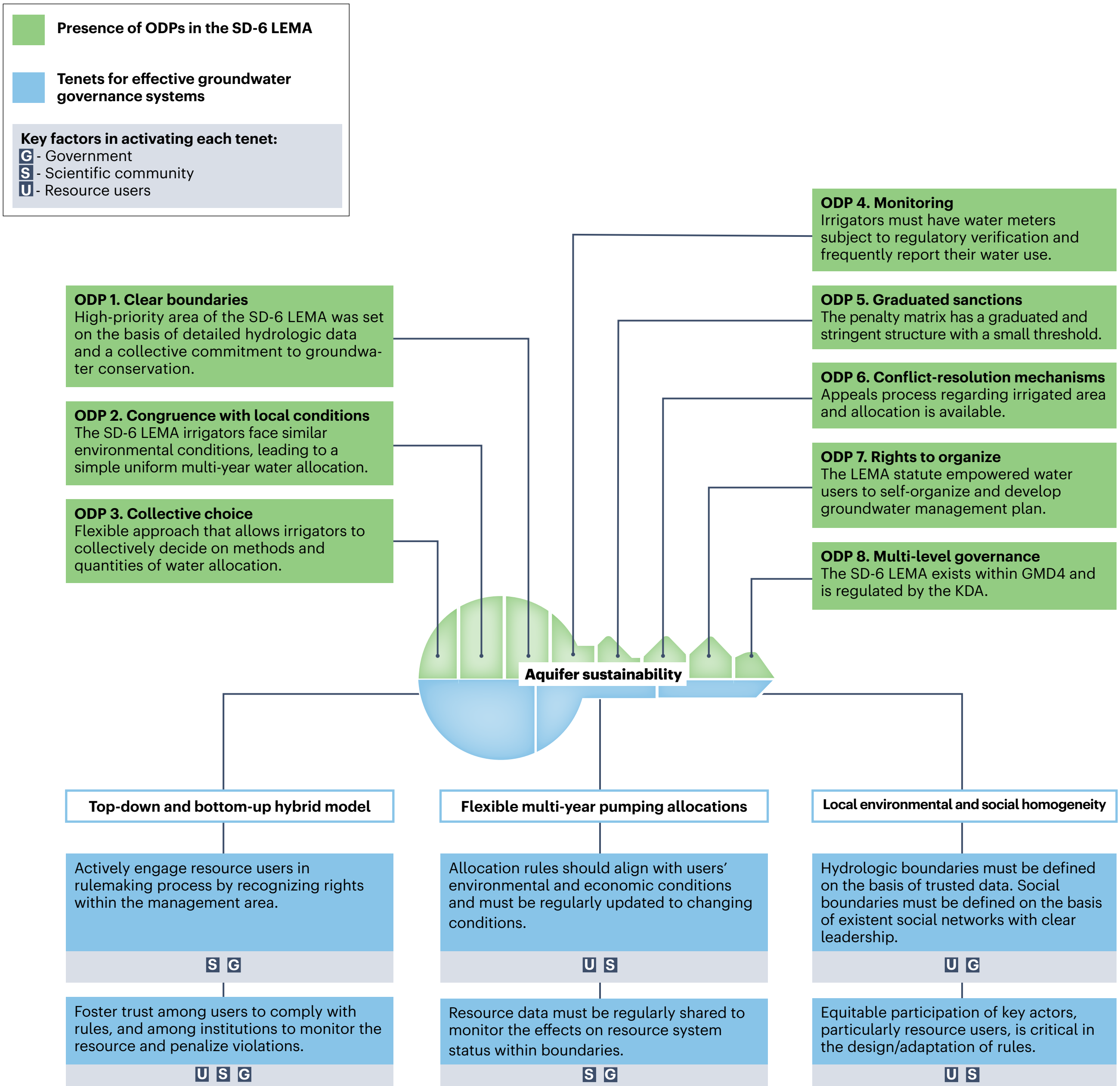

Fig. 4 | Tenets for effective groundwater governance. Top: the alignment of the SD-6 LEMA with the ODPs[48] for self-governance of common-pool resources. Bottom: transferable tenets, based on the key aspects of the SD-6 LEMA, that we assert can help address global challenges in groundwater conservation. Each tenet is associated with the key actors responsible for its implementation.

junior water rights to fulfil the demands of senior users, the SD-6 LEMA programme distributes the reduction in water consumption across all users, resulting in a more socially manageable burden. Fundamentally, the SD-6 LEMA extends the hydrologic and, therefore, economic viability of the aquifer. By combining these bottom-up regulations with top-down regulatory enforcement, the SD-6 LEMA provides assurances to irrigators that adherence to the rules will be universal, thus mitigating the pervasive 'free rider' dilemma encountered in numerous common-pool resource management endeavours[21].

Flexible multi-year pumping allocations

The SD-6 LEMA irrigators have greatly benefited from a flexible approach to meet reduction targets, defined as a 5 year cap on groundwater use. A multi-year approach, sometimes referred to as a 'soft cap'[43], offers irrigators greater flexibility to adapt their irrigation rates compared with strict annual limits on pumping. Research elsewhere indicates that multi-year allocation strategies outperform strict annual limits by mitigating production risks and enhancing farm profitability[43].

The SD-6 LEMA's approach was developed through numerous public hearings underpinned by a robust scientific foundation of publicly available groundwater use and water-level data. Since the early 1990s, all nondomestic pumping wells in the Kansas High Plains aquifer have been systematically metered, accompanied by clear reporting protocols and rigorous quality control measures. In addition, a network of monitoring wells was established, which has ensured widespread consensus regarding the fundamental scientific realities of aquifer depletion throughout western Kansas. By 2010, 99% of the nondomestic pumping wells in GMD4 had meters. Over the span of 4 years, 11 public hearings were convened to design the SD-6 LEMA multi-year allocations, grounded in local hydrological and economic considerations[44]. These meetings addressed stakeholder concerns regarding different approaches for designing water allocations, irrigation technologies, potential legal avenues for reducing pumping rates and penalties for violations. Thanks to this deliberative and transparent process, survey findings reveal that farmers perceive the regulations as clear and comprehensible[39].

Ultimately, multi-year flexibility provides irrigators the freedom to select technologies and crops that best suit their preferences. This approach, maintained in the renewals of the SD-6 LEMA (2018–2022, 2023–2027), has been enhanced by rewarding conservation efforts. Those who conserve more than the 20% reduction target are eligible for an ~13 cm [5 inch] carryover of unused allocation from the previous period. Moreover, the LEMA allows irrigators to pool their allocations across their pumping wells, an essential feature that provides additional flexibility for irrigators to tailor adaptation strategies to their farm's operations[25]. This flexibility has been warmly embraced, fostering a culture of experimentation among farmers and building adaptive capacity, in the form of banked water, for potential drought. For example, pumping restrictions have prompted consideration of sorghum and other crops, accompanied by the implementation of precision agriculture practices that aim to optimize management by reducing irrigation intensity and enhancing efficiency[23,35]. Innovations such as soil-water monitoring and computer-aided irrigation scheduling have further empowered irrigators to improve soil health, boost water storage capacity, optimize water extraction by crop roots and introduce drought-tolerant crop varieties[31].

Although the SD-6 LEMA provides flexibility, it also incorporates stringent civil penalty provisions. Irrigators are required to report their water use every 2 weeks. Failure to do so results in the presumption that the irrigator has utilized their maximum yearly allocation[27]. Penalties are imposed for violations based on a 4.93 Ml [4 acre-feet] threshold. Violations that exceed the 5 year allocation and are less than the threshold result in a fine of US$1,000 per day. Violations surpassing this threshold result in an automatic 2 year suspension of all associated water rights[25]. The suspension is carried out by locking the flowmeters and frequently checking the pump and whether the fields have been irrigated.

Local environmental and social homogeneity

Comanagement of groundwater resources requires that water users and higher-level government entities work in tandem to determine the management strategy and its implementation for a region. Because conflicting interests and disparate resources can pose challenges[17], designing comanagement approaches to encourage equitable participation is key to their effectiveness. In the SD-6 LEMA, this equitable participation was accomplished through the public rulemaking process described in the preceding and by limiting the pumping restrictions to an area with relatively homogeneous hydrological and economic conditions[44]. This alignment helped to integrate aquifer comanagement with existing regional social networks and provide local benefits to irrigators. The small size of the SD-6 LEMA probably supported its success, suggesting that groundwater conservation can be more effectively achieved through relatively small but carefully targeted conservation areas.

The success of the SD-6 LEMA was also supported by the adaptability of interconnected governance systems. This adaptability required collaboration among producers, GMD4 and both state and federal entities, including the US Department of Agriculture's Risk Management Agency (RMA), which oversees the federal crop insurance programme. The costs, eligibility criteria and advantages of different insurance plans vary, but all mandate adherence to good farming practices, which, for irrigated production, often require that irrigation should be consistent with historical applications—a requirement that can discourage water conservation[45]. To ensure that irrigators maintained access to insurance while conserving groundwater, the RMA devised a novel limited irrigation written agreement that could help farmers better manage the financial risks associated with lower yields due to reduced water use[46]. Despite the potential benefits, this reduced-irrigation insurance option has not gained traction among SD-6 LEMA irrigators because it has not been necessary (yields have not decreased considerably for most crops as shown in Fig. 3b) and due to its higher cost, narrower coverage and more-complex enrolment process. Nevertheless, the willingness of the RMA to provide a flexible accommodation to facilitate groundwater conservation provided reassurance to irrigators that they could maintain crop insurance coverage.

Evidence for Ostrom design principles

Many groundwater conservation initiatives fall short of achieving sustainable outcomes[41,47]. The SD-6 LEMA offers valuable insights for broader implementation of effective groundwater conservation approaches. To discern transferable tenets from the SD-6 LEMA experience, we employed a framework anchored in the eight Ostrom design principles (ODPs)[48] (top of Fig. 4), which have been demonstrated to lead to more sustainable use of common-pool resource systems and the adaptability of resource systems to local contexts[49]. Although these principles offer a structured approach to crafting groundwater governance strategies with global applicability, it is essential to acknowledge that there is no uniform solution[14,21]. Ultimately, successful collaborative governance relies on flexible institutional frameworks and collective action in a comanagement framework characterized by shared decision-making authority[17].

Within the SD-6 LEMA, irrigators formulated their own conservation rules, tailored to mirror the social–environmental dynamics of the region, encompassing similar climatic, hydrological and economic conditions (ODP 2). This was enabled by the state's required water-use monitoring (ODP 4) and reliable and trusted hydrological data from the policy-neutral Kansas Geological Survey, which laid the scientific foundation for introducing new regulations on resource usage. Effective monitoring processes and communication are indispensable for fostering trust among resource users. Without this trust, rational individuals typically lack the motivation to propose or adhere to new rules[48].

The success of the SD-6 LEMA demonstrates the need for collaboration to address the collective-action challenge inherent in establishing new regulations. Rather than embracing a simplistic dichotomy of top-down versus bottom-up approaches[50], the SD-6 LEMA integrated elements of both to achieve the ODPs. The KDA-DWR approval of the SD-6 LEMA (ODP 1) acknowledged and upheld irrigators' rights to devise local rules (ODP 7). In this bottom-up rulemaking process, irrigators collaborated to formulate and refine regulations for managing groundwater resources (ODP 3), and this innovative approach involved three key stakeholders—users (irrigators), the scientific community and the state government—forming a nested governance structure to address aquifer depletion (ODP 8).

Furthermore, LEMA rules were marked by a straightforward, consistent multi-year allocation of groundwater resources. Irrigators in the SD-6 LEMA have notably embraced a more rigorous penalty system (ODP 5) compared with similar conservation initiatives[21]. These penalties, although less graduated than those advocated by common-pool resource theories, suggest that the advantages of simplified regulations may outweigh the potential benefits of graduated sanctions[51]. In addition, the SD-6 LEMA offers an appeals process that fosters a consistent and shared interpretation of rules enforcement (ODP 6).

Transferable groundwater governance tenets

Drawing from the previously mentioned key aspects of the SD-6 LEMA (the hybrid integration of bottom-up rule development with top-down enforcement, the multi-year flexibility achieved through a 5 year cap and the focus on smaller areas of relatively homogeneous environmental and social conditions) and the alignment with ODPs, we suggest six tenets in three broad categories (bottom of Fig. 4) that we assert are required to adapt the success of the SD-6 LEMA to other groundwater-dependent agricultural regions. Transferring these tenets elsewhere requires close integration among the government, the scientific community and resource users. The government must ensure active engagement and equitable participation in the rulemaking process and compliance with rules, users must foster trust among themselves and institutions to comply with regulations and require the flexibility to experiment and build capacity for conservation, while the scientific community must conduct actionable and trusted research to share information about the status of the aquifer and the effectiveness of the rules.

This holistic approach encompasses the social, economic and scientific facets of sustainable management of common-pool resources. Socially, long-term strategies must encompass the widespread and often overlooked impacts of aquifer depletion on the broader community[52]. Economically, the sustainability of groundwater-dependent communities across generations hinges on their capacity to change from unsustainable groundwater usage to alternative economic paradigms, thereby diminishing future reliance on the resource[14,44]. From a scientific perspective, the development of decision support systems to inform transitions to reduced water usage requires collection of data on groundwater pumping, water levels, crop area and irrigation technology[21]. These systems can be used to assess integrated political, hydrological and economic responses to policy, facilitating the analysis of past policies' effects and the formulation of future policies[53]. Likewise, it is imperative to educate the local community about the status of its water resources. The efficacy of groundwater governance systems lies in disseminating information through such channels as geological surveys, agricultural extension services and peer networks to make the case for water conservation.

Although we highlight key transferable tenets for adapting the success of the SD-6 LEMA to other regions, replicating this success elsewhere will inevitably bring about challenges due to differing local conditions, including institutional frameworks (prevailing rules), social dynamics (community characteristics) and environmental conditions[14]. Institutional hurdles emerge when groundwater management plans are imposed by external entities rather than arising from a bottom-up process. Nevertheless, even externally imposed plans can integrate fundamental tenets gleaned from the SD-6 LEMA experience, emphasizing local adaptability, incentivizing collective action and establishing social and structural mechanisms that facilitate irrigators' adaptation while safeguarding their livelihoods[8].

Social challenges in promoting conservation may arise from limited hydrological knowledge of groundwater systems and lack of a collective sense of responsibility for aquifer depletion. For example, the successful SD-6 LEMA plan for pumping reductions relied heavily on access to reliable groundwater pumping and water-level data, information lacking in many regions[25]. Nonetheless, it is possible to make reasonable estimates of pumping reductions even with limited data[54], using such proxies as evapotranspiration to estimate pumping volumes[10,55]. In addition, garnering community support and a shared sense of responsibility for groundwater conservation can be challenging. For example, Kansas producers acknowledge the gravity of aquifer depletion but often do not feel personally accountable for it[39]. This perception could impede producer involvement in collective groundwater conservation efforts, highlighting the need to ensure equitable user participation in rule design and to effectively integrate bottom-up regulations with top-down enforcement mechanisms.

The success of the SD-6 LEMA highlights a promising approach: a collaborative governance framework empowered to set goals and oversee conservation commitments, while allowing for local flexibility to address specific challenges. The intricate interplay between social, economic and social dimensions of groundwater management underscores the importance of developing participatory strategies that bring together scientists, managers, policymakers and stakeholders. These collaborative endeavours not only foster the creation of collective knowledge and solutions, but also facilitate learning through the dissemination of information aimed at promoting water conservation[10,31]. The scientific and scholarly communities (for example, hydrogeology, agronomy, political science, sociology and law) can bolster these efforts by engaging in interdisciplinary research that connects environmental and social processes[56].

Insights and future research needs

Ensuring the sustainability and resilience of groundwater governance systems is paramount for addressing the global challenges surrounding food and water supplies. The complex issue of aquifer depletion defies a uniform solution, but examining the interconnected hydrological, social and economic factors that contribute to a successful groundwater conservation initiative offers valuable insights for other regions to emulate. The efficacy of comanagement hinges on striking a delicate balance between incentives and penalties, with accountability and transparency serving as fundamental elements of the established regulations[17]. In this Perspective, we delved into the critical elements underpinning the success of the SD-6 LEMA within a heavily depleted portion of the High Plains aquifer in the central United States. The SD-6 LEMA has proved effective by virtue of an innovative hybrid model that integrates bottom-up rule development by irrigators with top-down monitoring and enforcement by the state regulatory body. Tailoring rules to local social, economic and physical contexts has been pivotal and was enabled by the area's relatively small scale. This finding suggests that relatively small conservation areas may be more effective for common-pool resource management. Furthermore, the programme's implementation of multi-year irrigation quotas affords irrigators the flexibility to meet targets in a manner that suits their operational needs. Drawing from principles of common-pool resource management, we formulated a set of recommendations to replicate the success of the SD-6 LEMA across diverse regions. Adapting these guidelines to groundwater governance on a broader scale holds promise for shaping policies that bolster resilience amid fluctuating demands and stressors.

However, contemporary water challenges often transcend local boundaries, with groundwater usage influenced by external economic factors[9], necessitating a governance strategy that extends beyond the confines of the local level[52]. A crucial aspect warranting further exploration is how groundwater conservation programmes can reconcile the mismatch in scale between the global drivers fuelling depletion and the local communities bearing its direct consequences[57]. This endeavour may entail pioneering new theoretical frameworks and empirical investigations to unravel the interplay of governance structures across various scales. Enhanced sociohydrological modelling techniques, which fuse hydrological, agricultural and socioeconomic analyses into a unified framework, can facilitate this exploration[53]. However, translating the resulting insights into practical management strategies requires the recognition that irrigators are often motivated more by the sustainability of their communities and agricultural practices rather than the abstract notion of groundwater preservation[39]. The tenets for effective groundwater governance systems demonstrated by the SD-6 LEMA provide a blueprint for global groundwater conservation initiatives. By fostering interdisciplinary collaboration dedicated to actionable solutions, we can employ these principles to tackle the formidable challenge of aquifer depletion while mitigating adverse economic and social impacts.

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