



Groundwater Resource Management: Challenges, Sustainable Strategies, and Future Perspectives

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Abstract

Groundwater is the largest accessible store of unfrozen freshwater on Earth and the resource on which a substantial share of global drinking water supply and irrigated agriculture depends. Its management has nonetheless proved unusually difficult, because the resource is invisible, slow to respond, held in common and governed by institutions that were rarely designed for it. The analysis is organised around three questions: what the observational record shows about the scale and geography of groundwater stress, which management strategies have demonstrable evidence of effectiveness, and where the principal gaps between scientific understanding and management practice lie. Results are presented in six tables covering global abstraction and sectoral dependence, the depletion status of major aquifer systems, the drivers of stress, contaminants of concern, the evidence base for supply-side, demand-side and governance interventions, and documented cases of aquifer recovery. The synthesis indicates that depletion is spatially concentrated rather than universal, that quality degradation affects a larger population than quantity decline alone, and that the interventions with the strongest recovery evidence combine supply augmentation with binding limits on abstraction. Purely supply-side or purely regulatory responses perform poorly in isolation. The paper concludes that groundwater sustainability is constrained less by hydrological knowledge than by monitoring coverage, institutional capacity and the political economy of allocation, and it identifies priorities for future work.

Keywords: Groundwater management; aquifer depletion; water governance; managed aquifer recharge; groundwater quality; water sustainability; secondary data analysis

1. Introduction

1.1 Groundwater in the Global Water System

Groundwater constitutes by far the largest store of liquid freshwater on the planet, exceeding the combined volume of rivers, lakes and wetlands by several orders of magnitude. Its distinguishing physical characteristics are storage and inertia. Because aquifers accumulate recharge over years to millennia, they buffer societies against seasonal and interannual variability in rainfall, and it is this buffering function rather than the absolute volume of the resource that explains its economic importance. Where surface water fails during drought, groundwater continues to yield, and the resource therefore underpins agricultural and domestic security in precisely those periods when it is most needed (Gleeson et al., 2020).

The scale of dependence is substantial. Groundwater supplies drinking water to roughly half the global population and accounts for approximately forty per cent of the water used in irrigated agriculture, with the proportion far higher in arid and semi-arid regions (Scanlon et al., 2023). Its use expanded rapidly from the mid-twentieth century as cheap drilling technology, rural electrification and subsidised energy made individual abstraction feasible

for hundreds of millions of smallholders. That expansion was largely unplanned and, in most jurisdictions, effectively unregulated, producing a pattern of development in which the aggregate consequences of individually rational decisions became apparent only decades later.

Groundwater also performs ecological functions that are easily overlooked in accounting exercises focused on supply. Baseflow discharge sustains rivers, wetlands and springs through dry periods, and groundwater-dependent ecosystems are frequently the first casualties of abstraction, responding long before water tables fall to levels that concern well owners. de Graaf et al. (2019) estimated that a substantial proportion of pumped watersheds worldwide will pass critical environmental flow limits by the middle of the century, and Mukherjee et al. (2018) documented reduced baseflow contributing to summer drying of the Ganges. The resource is therefore not simply a reservoir to be drawn down but a component of a coupled surface-water and groundwater system whose depletion transfers costs to third parties and to the environment.

1.2 Emerging Pressures on Groundwater Systems

Four pressures now act on groundwater systems simultaneously. The first is intensified abstraction driven by population growth, dietary change and the expansion of irrigated cropping. Irrigation accounts for the overwhelming majority of groundwater use, and demand is inelastic in the short run because it is embedded in cropping decisions, capital investment in wells and pumps, and, in many countries, in energy and price-support policies that make water-intensive cultivation rational for the individual farmer. Dalin et al. (2017) demonstrated that a measurable share of non-renewable groundwater abstraction is embedded in internationally traded food, so that depletion in one basin is driven partly by consumption elsewhere.

The second pressure is climate change, which alters both recharge and demand. Its effects are strongly divergent rather than uniformly negative. Wu et al. (2020) found that projected changes in mid-latitude aquifer availability differ in sign between regions, and Cuthbert et al. (2019) showed that groundwater response to climate operates over very different timescales in humid and arid settings, with recharge in many drylands reflecting palaeoclimatic conditions rather than contemporary rainfall. The practical implication is that climate-related risk to groundwater cannot be generalised and must be assessed aquifer by aquifer.

The third pressure is quality degradation. Contamination arises from geogenic sources such as arsenic and fluoride mobilised by natural aquifer chemistry, and from anthropogenic sources including agricultural nitrate, salinity from irrigation return flows, industrial solvents and seawater intrusion in coastal aquifers. Podgorski and Berg (2020) estimated that a very large population, concentrated in Asia, is exposed to elevated arsenic concentrations in groundwater, and MacDonald et al. (2016) found that a majority of groundwater in parts of the Indo-Gangetic Basin is compromised by salinity or arsenic. Quality loss removes usable volume as effectively as depletion does, and it is frequently irreversible on management timescales.

The fourth pressure is institutional. Groundwater is a common-pool resource characterised by low excludability, diffuse users and invisible stocks, and the conventional regulatory model of licensing and enforcement performs poorly under these conditions. Molle and Closas (2020) reviewed the record of state-centred groundwater governance and concluded that it has been largely ineffective across a wide range of contexts, not because the instruments are poorly designed in principle but because the monitoring, enforcement and political conditions they presuppose are seldom present. This diagnosis frames the analysis that follows.

2. Literature Review

2.1 Global Assessments of Groundwater Depletion and Quality

The empirical literature on groundwater status has been transformed by two developments: satellite gravimetry and the compilation of in situ monitoring records at continental and global scale. Rodell et al. (2018) used observations from the Gravity Recovery and Climate Experiment to map emerging trends in global freshwater availability, identifying coherent regional patterns of terrestrial water storage change and attributing them to a combination of natural variability, climate change and direct human intervention. The GRACE record established that depletion signals in the world's most intensively pumped aquifers are large enough to be detected from orbit, which changed the political salience of the issue.

Satellite gravimetry nonetheless has limitations that the subsequent literature has worked to address. Its footprint is coarse, it measures total water storage rather than groundwater specifically, and its record is short relative to aquifer response times. Scanlon et al. (2023) argued for treating surface water and groundwater as a single interconnected resource and demonstrated that longer in situ monitoring records place the satellite era in a different light, revealing rising storage in some regions where short records suggest decline and vice versa. MacDonald et al. (2016) made a related point for the Indo-Gangetic Basin, showing from in situ observations that depletion there is more spatially localised than basin-scale satellite estimates imply, and that abstraction is in places sustained by recharge from irrigation losses.

The most comprehensive in situ synthesis to date is that of Jasechko et al. (2024), who analysed groundwater-level trends from approximately 170,000 monitoring wells across 1,693 aquifer systems in countries accounting for around three-quarters of global withdrawals. Their results are important in two respects. Rapid declines exceeding half a metre per year are widespread in the twenty-first century and are concentrated in dry regions with extensive croplands; and declines have accelerated over recent decades in roughly thirty per cent of the regional aquifers examined. Equally significant, the study identified cases in which depletion trends reversed following policy change, managed aquifer recharge or surface-water substitution, establishing that recovery is achievable rather than merely theoretical.

Quantitative estimates of global depletion vary considerably according to method. Bierkens and Wada (2019), reviewing the field, reported a wide spread across model-based, water-balance and volumetric approaches, reflecting genuine uncertainty in recharge estimation, abstraction reporting and specific yield rather than simple disagreement. A parallel literature documents the consequences of depletion: land subsidence affecting a substantial share of the

global population (Herrera-García et al., 2021), wells running dry where drilling depth has not kept pace with declining water tables (Jasechko & Perrone, 2021), and the progressive substitution of deeper drilling for demand management, which Perrone and Jasechko (2019) characterised as an unsustainable stopgap that raises costs, increases the risk of encountering poor-quality water and postpones rather than resolves the underlying imbalance.

2.2 Governance, Institutions and Sustainable Management Strategies

The second body of literature turns from diagnosis to response. Its central finding is that the binding constraint on groundwater sustainability is institutional rather than technical. Gorelick and Zheng (2015) framed the management challenge as one of coupling hydrological understanding to decision processes operating at different scales and time horizons, and noted that the technical capacity to model aquifer response has long exceeded the institutional capacity to act on model outputs. Elshall et al. (2020) developed this argument through a review of science and policy interactions, showing that sustainability definitions are themselves contested: what counts as sustainable yield depends on which externalities, which time horizon and whose interests are admitted into the calculation.

Closas and Villholth (2020) set out the core concepts of groundwater governance, distinguishing it from management in the narrow sense and emphasising the roles of legal frameworks, information systems, participatory institutions and policy coherence across the water, energy and agriculture sectors. Their analysis draws attention to a recurring failure: groundwater policy is frequently undermined by energy and agricultural policy operating in the opposite direction, so that a state may simultaneously regulate abstraction and subsidise the electricity that makes abstraction cheap. Molle and Closas (2020) extended this critique, arguing that state-centred regulatory approaches have largely failed because they assume monitoring and enforcement capacity that does not exist and because they confront users who vastly outnumber regulators.

Against this, a body of work documents interventions that have produced measurable results. Dillon et al. (2019) reviewed six decades of managed aquifer recharge, showing sustained global growth in application and identifying the conditions under which it succeeds, principally the availability of surplus surface water, suitable hydrogeology and adequate pre-treatment. They also emphasised that managed recharge remains small relative to total abstraction and therefore cannot substitute for demand management at aquifer scale. The recovery cases identified by Jasechko et al. (2024) point in the same direction: reversal was observed where recharge or surface-water substitution was combined with constraints on pumping, not where either was applied alone.

Two further themes recur. The first concerns participatory and community-based management, which the literature treats with qualified optimism, noting that local monitoring and collective rule-setting can achieve compliance that formal regulation cannot, but that outcomes depend on prior social organisation and on secure state backing for locally agreed rules. The second concerns conjunctive management of surface water and groundwater, which follows directly from the hydrological connectivity established by de Graaf et al.



(2019) and Mukherjee et al. (2018) and which is increasingly treated as the default framing rather than a specialised technique.

3. Research Methodology

3.1 Research Design

This study employs a secondary-data research design, combining a structured review of peer-reviewed literature with the compilation and comparative analysis of published quantitative datasets on groundwater abstraction, storage change, quality and management interventions. A secondary-data approach was chosen because the research questions concern global and regional patterns that no primary field campaign could observe at the required scope, and because the relevant observational networks are operated by national agencies and international organisations whose published outputs constitute the best available evidence base.

Three research questions guided the work. First, what does the compiled observational record indicate about the scale, geography and drivers of groundwater stress? Second, which management strategies have documented evidence of effectiveness, and under what conditions? Third, where do the principal gaps lie between the state of scientific understanding and the state of management practice?

3.2 Sources of Secondary Data

Three categories of secondary source were used. The first comprises peer-reviewed journal articles published between 2015 and 2024, identified through structured searches of Scopus, Web of Science and Google Scholar using combinations of the terms groundwater depletion, groundwater management, aquifer sustainability, groundwater governance, managed aquifer recharge and groundwater quality. Twenty studies meeting the inclusion criteria form the evidentiary core of the paper. The second category comprises published global datasets and assessment reports, including satellite gravimetry products, national groundwater monitoring summaries and international water-use compilations, drawn on for the abstraction and storage figures reported in Section 4. The third category comprises documented case material on management interventions, taken from the reviewed studies rather than from primary agency records.

Studies were retained where they addressed groundwater quantity, quality, governance or management at regional to global scale; reported quantitative results or systematic qualitative synthesis; described their methods in reproducible outline; and appeared in a peer-reviewed journal indexed in at least one of the databases searched. Purely local case studies without transferable findings, and modelling papers without observational validation, were excluded.

3.3 Data Extraction and Analytical Framework

A structured extraction template recorded, for each source, the geographical scope, the observational or modelling basis, the period covered, the reported quantitative findings with their stated uncertainty, and the management implications drawn by the authors. Extracted material was then organised within a three-part analytical framework distinguishing the state of the resource, the drivers of change, and the response options available to managers. This

framework, rather than the disciplinary origin of each source, determines the structure of Section 4.

Because the compiled figures originate in studies using different methods, periods and definitions, they are reported as ranges or as indicative central values with the source identified, and comparisons are made between categories rather than between individual point estimates. Where estimates conflict, both are reported and the methodological reason for the divergence is stated. No new statistical modelling was performed; the analytical contribution of the paper lies in the systematic organisation and comparative interpretation of evidence that is presently dispersed across hydrology, remote sensing, agricultural economics and public policy literatures.

3.4 Limitations of the Secondary-Data Approach

Four limitations should be borne in mind. Monitoring coverage is highly uneven: the global well networks synthesised by Jasechko et al. (2024) cover countries responsible for approximately three-quarters of withdrawals, leaving substantial parts of Africa, central Asia and South America thinly represented, so that apparent global patterns partly reflect where measurement occurs. Reported abstraction figures depend on national statistics whose quality varies widely and which frequently estimate rather than measure informal rural pumping. Definitional inconsistency persists in terms such as depletion, sustainable yield and safe yield, which are used differently across the literature. Finally, publication and reporting bias favours documented successes and dramatic declines over the large intermediate category of aquifers that are neither in crisis nor demonstrably well managed. The findings are therefore presented as a structured synthesis of available evidence rather than as a comprehensive global inventory.

4. Results

4.1 Global Groundwater Abstraction and Sectoral Dependence

Table 1 compiles indicative figures on groundwater abstraction and dependence for the principal using regions. The distribution is strikingly concentrated: a small number of countries account for the majority of global abstraction, and within those countries abstraction is concentrated in a small number of intensively irrigated basins.

Table 1. Indicative groundwater abstraction and sectoral dependence for major using regions (compiled from published assessments)

Region / country	Estimated abstraction (cubic km per year)	Share of national water withdrawal	Dominant use sector	Principal form of dependence
India	230 - 250	~60%	Irrigation (~89%)	Rural drinking water and dry-season irrigation
United States	110 - 115	~25%	Irrigation	High Plains and



Region / country	Estimated abstraction (cubic km per year)	Share of national water withdrawal	Dominant use sector	Principal form of dependence
			(~70%)	Central Valley agriculture
China	105 - 115	~19%	Irrigation (~55%)	North China Plain agriculture and industry
Pakistan	60 - 65	~30%	Irrigation (~95%)	Conjunctive irrigation in the Indus basin
Iran	55 - 60	~55%	Irrigation (~85%)	Arid-zone agriculture and municipal supply
Mexico	~30	~38%	Irrigation (~70%)	Urban supply and irrigated agriculture
Saudi Arabia	22 - 25	~85%	Irrigation (~85%)	Non-renewable fossil aquifer abstraction
European Union	50 - 55	~25%	Public supply (~60%)	Municipal drinking water provision
Sub-Saharan Africa	10 - 15	~15%	Domestic supply	Rural water points and small-scale irrigation
World total	900 - 1,000	~26%	Irrigation (~70%)	About half of drinking water; ~40% of irrigation

Two features of the table merit emphasis. First, the dominance of irrigation means that groundwater policy is in practice agricultural policy, and instruments that do not engage cropping patterns, energy pricing and output markets are unlikely to alter abstraction materially. Second, the countries with the highest absolute abstraction are not uniformly those with the highest stress, because abstraction must be read against recharge. India and the United States both abstract heavily, but the sustainability implications differ sharply between the alluvial aquifers of the eastern Gangetic plain, where recharge is abundant, and the largely fossil storage of the southern High Plains.

4.2 Status of Major Aquifer Systems

Table 2 summarises the reported status of major aquifer systems that recur in the reviewed literature.

Table 2. Reported depletion status and principal stressors of selected major aquifer systems

Aquifer system	Region	Reported trend	Dominant stressor
North China Plain	China	Long-term decline; partial stabilisation since surface-water transfer	Irrigation and industrial abstraction
Indo-Gangetic Basin	India, Pakistan	Rapid decline in the north-west; stable to rising in the east	Subsidised energy and paddy-wheat cropping
High Plains (Ogallala)	United States	Severe decline in the south; broadly stable in the north	Irrigated cereal production over fossil storage
Central Valley	United States	Episodic severe decline during drought periods	Drought-period substitution for surface water
Saq and related aquifers	Saudi Arabia	Continuous decline with negligible modern recharge	Fossil-water irrigation
Guarani Aquifer System	South America	Broadly stable at system scale	Localised urban and industrial abstraction
Upper Guadiana basin	Spain	Historic decline followed by partial recovery	Irrigation abstraction; subsequent policy reform
Chao Phraya basin	Thailand	Decline reversed following regulation	Urban and industrial abstraction
Nubian Sandstone	North Africa	Slow depletion of fossil storage	Irrigation and municipal supply
Bengal Basin	Bangladesh, India	Quantity broadly stable; quality severely impaired	Arsenic mobilisation in shallow aquifers

The pattern that emerges is one of concentration rather than universality. Severe depletion is confined largely to arid and semi-arid regions with extensive irrigation, which is consistent with the finding of Jasechko et al. (2024) that rapid declines cluster in dry regions with

substantial cropland. Several major aquifers are stable or recovering, and treating groundwater depletion as a uniform global crisis obscures both the geography of the problem and the existence of counter-examples from which management lessons can be drawn.

4.3 Drivers and Manifestations of Groundwater Stress

Table 3 organises the drivers of groundwater stress identified across the reviewed literature, distinguishing the underlying driver from its observable manifestation and from the management lever that acts on it.

Table 3. Drivers of groundwater stress, their manifestations and corresponding management levers

Driver	Observable manifestation	Typical response lag	Principal management lever
Expansion of irrigated agriculture	Declining water tables; progressive well deepening	Years to decades	Cropping policy and irrigation water accounting
Energy and output subsidies	Abstraction beyond the economic optimum	Immediate to years	Energy tariff reform and abstraction metering
Population and urban growth	Concentrated well fields and cones of depression	Years	Conjunctive supply and urban demand management
Climate variability and change	Altered recharge; drought-period substitution	Years to centuries	Adaptive allocation rules and buffer storage
Coastal over-abstraction	Seawater intrusion and salinisation	Years to decades; largely irreversible	Abstraction limits and barrier recharge
Compaction of fine-grained aquifers	Land subsidence and infrastructure damage	Decades; irreversible	Depth-specific restriction of pumping
Surface-water connectivity	Baseflow reduction; wetland and spring loss	Months to decades	Environmental flow standards
Agricultural and industrial loading	Nitrate, salinity and solvent contamination	Decades	Source control and land-use zoning
Weak institutional capacity	Unregistered wells and unenforced limits	Continuous	Governance reform, registration and monitoring

The table makes explicit a point that is often lost in policy discussion: most manifestations of stress are observed at a considerable lag behind the driver that produces them, and several of the management levers act on the driver rather than on the manifestation. Subsidence, seawater intrusion and ecosystem loss are in whole or part irreversible, which means that management responses triggered by observed damage are necessarily too late for the damage already incurred.

4.4 Groundwater Quality Challenges

Table 4 summarises the principal contaminants of concern reported in the reviewed literature, distinguishing geogenic from anthropogenic origins.

Table 4. Principal groundwater contaminants, sources, affected regions and management implications

Contaminant	Origin	Principal affected regions	Implication for use	Typical management response
Arsenic	Geogenic	South and South-East Asia; parts of South America	Chronic toxicity and carcinogenicity	Source substitution; blending; point-of-use treatment
Fluoride	Geogenic	India, East African Rift, parts of China	Dental and skeletal fluorosis	Defluoridation; alternative sources
Salinity and total dissolved solids	Geogenic and irrigation return flow	Arid irrigated basins; coastal zones	Loss of potable and irrigation suitability	Drainage management; leaching; blending
Seawater intrusion	Abstraction induced	Coastal aquifers worldwide	Permanent loss of the freshwater lens	Abstraction limits; barrier recharge
Nitrate	Fertiliser and sanitation	Intensively farmed regions globally	Infant health risk; ecosystem effects	Nutrient management; protection zones
Uranium and trace elements	Geogenic, abstraction enhanced	Semi-arid alluvial aquifers	Chronic toxicity	Monitoring; well siting; treatment
Industrial	Anthropogenic	Industrial and peri-	Long-lived	Containment;

Contaminant	Origin	Principal affected regions	Implication for use	Typical management response
solvents and organics	point sources	urban zones	contaminant plumes	remediation; land-use control
Pathogens	Sanitation and surface leakage	Shallow wells in unconsolidated aquifers	Waterborne disease transmission	Wellhead protection; sanitary sealing

Quality degradation deserves greater weight in management frameworks than it customarily receives. Geogenic arsenic and fluoride affect very large populations, are frequently mobilised or concentrated by abstraction itself, and cannot be remediated at aquifer scale by any presently available technology, so that the response is confined to source substitution, blending and point-of-use treatment (Podgorski & Berg, 2020). Anthropogenic contamination by nitrate, salinity and industrial compounds is in principle preventable but persists for decades because of long unsaturated-zone travel times, so that concentrations continue to rise for a generation after the causal practice has ceased. In both cases, quality loss removes usable volume as surely as depletion does, and an aquifer assessment framed solely in terms of storage change will systematically understate the loss of the resource.

4.5 Evidence on Sustainable Management Strategies

Table 5 assembles the evidence on the principal categories of management intervention, classified as supply-side, demand-side or governance measures.

Table 5. Sustainable groundwater management strategies, mechanisms, evidence of effectiveness and limitations

Strategy	Category	Mechanism	Evidence of effectiveness	Principal limitation
Managed aquifer recharge	Supply side	Infiltration or injection of surplus surface or treated water	Strong; six decades of documented growth and local recovery	Requires surplus water and suitable hydrogeology
Surface-water substitution and transfer	Supply side	Replaces groundwater with imported surface supply	Strong; associated with several documented recovery cases	High capital cost; pressure transferred to donor basin
Rainwater harvesting and check structures	Supply side	Localised augmentation of recharge	Moderate; benefits largely local and rainfall dependent	Limited basin-scale effect; downstream

Strategy	Category	Mechanism	Evidence of effectiveness	Principal limitation
				flow reduction
Irrigation efficiency technology	Demand side	Reduces water applied per unit area	Mixed; gains frequently offset by area expansion	Rebound effect can raise net consumption
Crop diversification and calendars	Demand side	Shifts demand toward less water-intensive crops	Moderate to strong where market support exists	Requires price and procurement reform
Energy tariff and reform metering	Demand side	Removes the incentive for marginal abstraction	Strong where implemented	Politically difficult; distributional impacts
Abstraction licensing and caps	Governance	Legal ceiling on withdrawal volumes	Weak implementation without enforcement capacity	Users vastly outnumber regulators
Participatory community management	Governance	Local monitoring and collective rule setting	Moderate; contingent on prior social organisation	Fragile without state backing for local rules
Water markets and tradable rights	Governance	Reallocates water toward higher-value uses	Context specific; effective in well-monitored settings	Requires accurate measurement and enforceable rights
Conjunctive surface and groundwater management	Integrated	Uses the aquifer as buffer storage across wet and dry years	Strong conceptual and growing empirical support	Institutional fragmentation between agencies

Three findings follow from the assembled evidence. Supply-side interventions such as managed aquifer recharge have the strongest technical evidence base and the clearest engineering pathway, but their aggregate volume remains small relative to abstraction, so that they modify local water tables more readily than basin-scale balances (Dillon et al., 2019). Demand-side interventions act directly on the imbalance and are therefore the only category

capable of restoring equilibrium at scale, but they impose visible and immediate costs on identifiable users and consequently face the greatest political resistance. Governance interventions determine whether the other two categories function at all, yet the reviewed evidence indicates that formal regulatory frameworks frequently fail in implementation (Molle & Closas, 2020). The practical inference is that intervention categories are complementary rather than substitutable.

4.6 Documented Cases of Aquifer Stabilisation and Recovery

Table 6 compiles cases in which groundwater declines have been arrested or reversed, drawn principally from the recovery analysis of Jasechko et al. (2024) and from the managed recharge literature.

Table 6. Documented cases of groundwater stabilisation or recovery and the interventions associated with them

Location	Intervention	Reported outcome	Key enabling condition
Chao Phraya basin, Thailand	Abstraction charges and licensing of urban and industrial wells	Long-term decline arrested; levels recovering	Concentrated and metered user base
Tucson basin, Arizona, USA	Managed aquifer recharge using imported surface water	Water-table recovery in recharge-influenced areas	Reliable imported supply and legal recharge credits
North China Plain, China	Inter-basin surface-water transfer with abstraction restriction	Slowing of decline and localised recovery	State capacity for infrastructure and enforcement
Upper Guadiana basin, Spain	Abstraction reduction and well buy-back under policy reform	Partial recovery after decades of decline	Legal framework with compensation funding
Saurashtra, Gujarat, India	Decentralised recharge structures with cropping change	Local water-table stabilisation reported	Community participation and suitable hydrogeology
Central Valley, California, USA	Statutory basin sustainability plans under state legislation	Framework established; outcomes still emerging	Statutory mandate with local implementation

The common structure of these cases is instructive. In each, an alternative supply was made available and abstraction from the stressed aquifer was simultaneously constrained, whether by regulation, by pricing or by the physical substitution of a surface source. No case in the compiled set shows recovery achieved by supply augmentation alone. The cases also share a second feature that is easily overlooked: all occur in settings with functioning monitoring



networks, without which neither the intervention could have been targeted nor the recovery detected. Monitoring is therefore not merely an evidentiary adjunct to management but a precondition for it.

5. Discussion

The evidence assembled in Section 4 supports four interpretive conclusions. The first concerns the geography of the problem. Groundwater stress is concentrated rather than universal, clustering in arid and semi-arid regions with extensive irrigation, and coexisting with stable and even recovering conditions elsewhere (Jasechko et al., 2024; Scanlon et al., 2023). This has direct implications for policy design. A globally uniform framing invites globally uniform prescriptions, whereas the observational record indicates that the binding constraint differs between basins: abstraction volume in the North China Plain, quality in much of the Bengal basin, energy pricing in north-western India, and allocation rules under conditions of surplus in parts of northern Europe.

The second conclusion concerns the relationship between knowledge and action. The reviewed literature demonstrates that hydrological understanding of aquifer behaviour, and the capacity to observe it, have improved substantially over the past decade through satellite gravimetry, in situ network synthesis and coupled modelling. Management outcomes have not improved commensurately. Gorelick and Zheng (2015), Elshall et al. (2020) and Molle and Closas (2020) converge, from different starting points, on the conclusion that the deficit is institutional. Regulatory frameworks presuppose monitoring and enforcement capacity that is frequently absent; sustainability targets are contested because the underlying value judgements are left implicit; and groundwater policy is routinely contradicted by energy and agricultural policy pursuing other objectives. Improved science is a necessary but plainly insufficient condition for improved management.

The third conclusion concerns the treatment of quality. Depletion dominates the policy conversation because it is quantifiable, satellite-observable and dramatic, whereas quality degradation is diffuse, locally variable and often geogenic in origin. Yet the population affected by unsafe groundwater quality is very large, the effects are frequently irreversible on management timescales, and abstraction itself contributes to mobilisation and intrusion (MacDonald et al., 2016; Podgorski & Berg, 2020). An assessment framework that measures sustainability in terms of storage change alone will register an aquifer as adequately managed while the usable fraction of its water is progressively lost.

The fourth conclusion concerns externalities and the distribution of costs. Depletion transfers costs to parties who do not participate in the abstraction decision: to ecosystems through baseflow reduction (de Graaf et al., 2019; Mukherjee et al., 2018), to future users through storage loss, to shallow well owners through deepening water tables (Jasechko & Perrone, 2021), to urban infrastructure through subsidence (Herrera-García et al., 2021), and, through embedded trade in water-intensive commodities, across national boundaries (Dalin et al., 2017). Progressive deepening of wells, which Perrone and Jasechko (2019) identify as the dominant adaptive response, is regressive in effect, since it is available to those with capital and unavailable to those without. Management frameworks that address only aggregate



volumes will therefore not address the distributional consequences of depletion, which are frequently what makes it politically intractable.

6. Conclusion

This paper has examined the challenges facing groundwater resource management, the strategies available to address them and the prospects for sustainable use, drawing on a secondary-data synthesis of twenty peer-reviewed studies published between 2015 and 2024 together with published global datasets on abstraction, storage change and water quality.

Four principal conclusions emerge. Groundwater stress is spatially concentrated rather than globally uniform, occurring predominantly in arid and semi-arid regions with intensive irrigated agriculture, and it coexists with stable and recovering conditions in other regions from which management lessons can be drawn. Quality degradation constitutes a challenge of comparable magnitude to depletion, affects very large populations, is frequently irreversible on management timescales, and is systematically underweighted in assessment frameworks built around storage change. The interventions with documented evidence of arresting or reversing decline invariably combine supply augmentation with binding constraints on abstraction; no compiled case demonstrates recovery through supply-side measures alone. And the binding constraint on sustainable management is institutional rather than scientific, residing in monitoring coverage, enforcement capacity, policy coherence across the water, energy and agriculture sectors, and the political economy of allocating a resource whose users vastly outnumber those charged with regulating them.

Two implications follow for practice. Monitoring should be treated as infrastructure rather than as research activity, since every documented recovery case occurred in a setting with a functioning observational network and no aquifer can be managed to a target that cannot be measured. And groundwater policy should be designed jointly with energy and agricultural policy, because instruments that regulate abstraction while subsidising its principal input will continue to be neutralised.

7. Future Work and Perspectives

Four priorities for future work follow from the gaps identified in this synthesis.

The first is the extension of monitoring coverage. The global in situ record remains concentrated in high-income and large middle-income countries, leaving much of sub-Saharan Africa, central Asia and parts of South America thinly observed. Because apparent global patterns partly reflect where measurement occurs, expansion of monitoring in under-observed regions is a research priority as well as an operational one. Low-cost telemetered sensors, crowd-sourced well observations and the integration of drilling records with formal networks all merit systematic evaluation for accuracy and sustainability of operation.

The second is the integration of quality and quantity within a single assessment framework. Present practice assesses storage change and contamination through separate literatures, separate institutions and separate indicators, despite their physical coupling through abstraction-induced mobilisation, seawater intrusion and irrigation return flow. Development of composite indicators expressing usable rather than merely available groundwater, and their

testing against basins where both dimensions are well observed, would materially improve the diagnosis of aquifer condition.

The third is systematic evaluation of governance interventions. The literature contains many descriptive accounts of participatory management, abstraction licensing, energy pricing reform and water markets, but few designs capable of attributing outcomes to interventions. Comparative studies employing matched basins, staged implementation or difference-in-differences designs would allow the field to move from documenting what has been attempted to establishing what works, and under which enabling conditions.

The fourth is the coupling of hydrological and socio-economic modelling under climate uncertainty. Given the divergent regional projections identified by Wu et al. (2020) and the long and variable response times documented by Cuthbert et al. (2019), robust management requires models that represent farmer behaviour, energy costs, crop choice and institutional response alongside aquifer physics. Advances in this direction would support the design of adaptive management rules that remain defensible across a range of climate futures rather than optimal under a single projection. Progress on these four fronts would narrow the gap, identified throughout this paper, between what is known about aquifers and what is done about them.

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