PERSPECTIVES PAPER

Global Water Partnership

The links between land use and groundwater

– Governance provisions and management strategies to secure a 'sustainable harvest'

Groundwater is an increasingly important resource for urban and rural potable water supply, irrigated agriculture, and industry, in addition to its natural environmental role of sustaining river flows and aquatic ecosystems. But major changes in land use that impact groundwater are taking place, as a consequence of population growth, increasing and changing food demands, and expanding biofuel cultivation. The link between land use and groundwater has long been recognised, but has not been widely translated into integrated policies and practices. This paper argues that a common understanding of groundwater–land and land–groundwater interaction is needed to facilitate cross-sector dialogue on governance needs and management approaches, targeted at sustaining water resources and enhancing land productivity. Sharply focused land-use management measures can produce significant groundwater quality and quantity benefits at relatively modest cost, and improving integrated governance will be crucial to ensuring an acceptable harvest of both food and groundwater from the available land. This paper outlines available technical tools to identify priority land areas for groundwater protection and appraises institutional and policy provisions to allow their application.

A GWP Perspectives Paper is intended to galvanise discussion within the network and the larger water and development community. Feedback will contribute to future GWP Technical Committee publications on related issues. This paper was written by Prof Dr Stephen Foster (Senior Advisor, Global Water Partnership) and Dr Jan Cherlet (Secretariat, International Land Coalition).

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About Global Water Partnership

The Global Water Partnership (GWP) vision is for a water secure world.

Our mission is to advance governance and management of water resources for sustainable and equitable development.

GWP is an international network that was created in 1996 to foster the implementation of integrated water resources management: the coordinated development and management of water, land, and related resources in order to maximise economic and social welfare without compromising the sustainability of ecosystems and the environment.

The Network is open to all organisations which recognise the principles of integrated water resources management endorsed by the Network. It includes states, government institutions (national, regional, and local), intergovernmental organisations, international and national non-governmental organisations, academic and research institutions, private sector companies, and service providers in the public sector.

The Network has 13 Regional Water Partnerships, 84 Country Water Partnerships, and 3,000 Partners located in 172 countries.

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Groundwater Resources and Irrigated Agriculture – Making a Beneficial Relation More Sustainable (2012)
Urban Groundwater – Policies and Institutions for Integrated Management (2013)
The links between land use and groundwater – Governance provisions and management strategies to secure a 'sustainable harvest' (2014)

Photos: Mostphotos

Contents

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1 Why does land–groundwater interaction matter?

Every land-use decision and practice has a water-resource footprint. Although this close linkage has long been recognised it has not, as yet, been widely translated into management practice through integrated policies (IFAD, 2010). The linkage is particularly important for groundwater governance and management, because land-use change can have long lasting, and in some cases, irreversible impacts on aquifers (Table 1). Some of the more significant changes include clearing natural vegetation and forests, converting pasture to arable land, extending the frontier of irrigated agriculture, intensifying both dryland and irrigated agriculture, introducing biofuel cropping, and reforestation and afforestation with commercial woodland[1].

1.1 *Groundwater – an important but vulnerable resource*

Globally groundwater is estimated to provide some 36 percent of all potable water supply, 43 percent of water used for irrigated agriculture, and 24 percent of direct industrial water supply (Döll et al., 2012). Groundwater also plays a key role in

Table 1 Summary of land-use impacts on groundwater recharge +

Impact of land use on recharge	Influence on		Comments
	Recharge rate	Recharge quality	
Deforestation (clearing native vegetation)	significant increases on flat ground from initially very low rates in arid areas	normally acceptable, but in arid climates may result in mobilisation of salts from sub-soil zone	on sloping ground, risk of soil erosion and eventual loss of recharge
Pasture	considered to be 'normal rate' especially in temperate climates	generally excellent and usually appropriate land use for waterwell protection zones	increasing grazing intensity will eventually trigger large nutrient losses
Dryland farming	ploughing-in pasture and existence of fallow land results in some increase in recharge	at low intensity good, but ploughing-in pasture can produce a flush of nutrient losses	intensification of crop production can lead to elevated agro-chemical leaching
Irrigated cropping (from surface-water sources)	substantial increases in all cases, especially marked where flood irrigation practised	risk of diffuse pollution from nutrients and pesticides, depending on agro-husbandry	additional hazard arises from biofuel crops or if wastewater is used for irrigation
Afforestation or reforestation	significant reduction, especially where non-deciduous species involved	slight tendency towards increased salinity in some instances	forested areas usually appropriate land use for waterwell protection zones
Urbanisation ++	increases from leaking water mains and in-situ sanitation much greater than reductions due to making land surface impermeable	major pollution hazard from nitrogen compounds, synthetic organic chemicals and sometimes pathogens and salinity	level of pollution hazard varies quite widely depending on style of urbanisation and hydrogeological setting

+ Open-cast mining and hydrocarbon exploitation can, under some circumstances, have a serious impact on groundwater but as they occupy much smaller land areas they are thus not included.

++ Urbanisation is taken to include industrial development, which if not subject to appropriate controls for handling chemicals and effluents results in severe land contamination accompanied by serious groundwater pollution where vulnerable aquifers are present.

[1] Recent GWP Perspectives Papers (of 2012 and 2013 respectively) have discussed the related issues of (a) groundwater irrigation sustainability and the long-term threat to agricultural production from excessive extraction (resulting partly from perverse levels of rural electricity or diesel fuel subsidy for waterwell pumps and from price guarantees for the most water-consuming crops) and (b) groundwater under large-scale urban development for which a fully integrated management approach is necessary.

maintaining healthy aquatic ecosystems and in sustaining environmental river flows. Although comprehensive statistics on groundwater use are not available, other estimates suggest that in 2010 global withdrawals exceeded 900 km^3 (Margat and Gun, 2013). Withdrawal intensity varies widely, and reaches the highest level across large areas of Bangladesh, China, India, Iran, and Pakistan, and more locally in the European Union, Mexico, the Middle East, North Africa, and USA (Foster et al., 2013a).

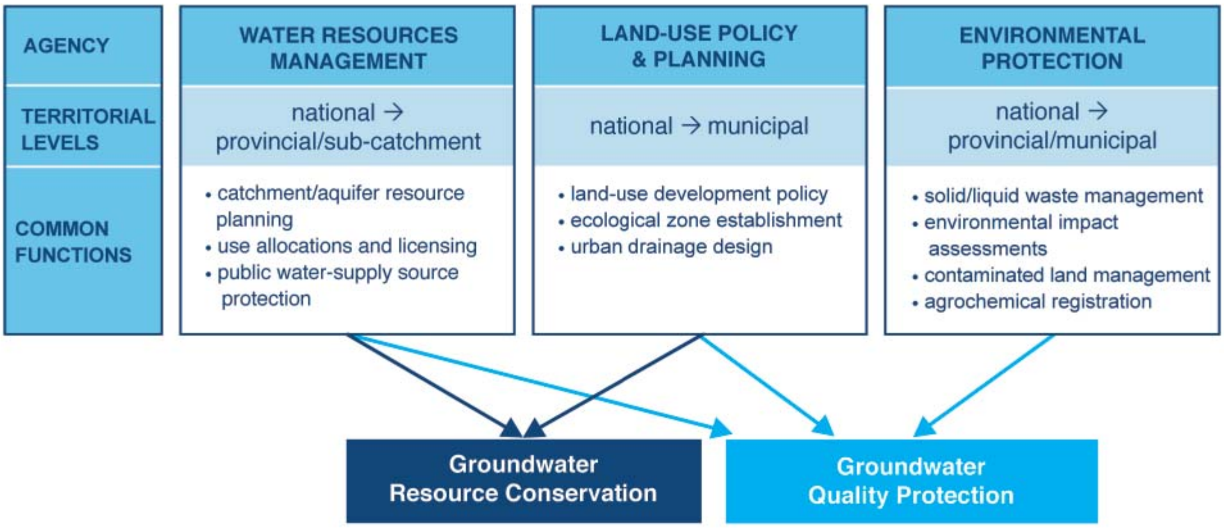
The social value of groundwater cannot be gauged solely by the volume of withdrawals. Compared to surface water, groundwater often brings greater economic benefits per unit volume because of its ready local availability, potential for scaling to demand, superior reliability during drought, and generally good quality meaning it requires minimal treatment.

Anthropogenic impacts on groundwater systems, some of which are irreversible, have increased markedly over the past 50 years as a result of massive exploitation for irrigated agriculture and urban water supply, and radical land-use change in many aquifer recharge zones.

Concerns about resource sustainability, quality degradation and impacts on ecosystems have increased. But despite notable technical advances it is still not possible to provide a detailed global assessment of the status of groundwater resources because of their widespread distribution, inadequate investment in monitoring, hydrogeological variability, and the consequent difficulty of aggregating available data (Foster et al., 2013a). All too commonly, groundwater resources have, in effect, been 'abandoned to chance' and 'business-as-usual' will further degrade the resource base.

Proactive campaigns, significant investments, and integrated actions to conserve groundwater are widely required. These must include land-use management measures to facilitate groundwater recharge and to protect groundwater quality at a range of geographical scales from local to district, provincial, and national level. Land-use policy and planning occupies a pivotal, but all too often ignored, position in the governance of groundwater resource conservation and quality protection (Figure 1).

Figure 1 Typical government agency functions in relation to groundwater resources



1.2 Land-use change – its scale and drivers

Over the past 250 years more than half the global ice-free land has been directly modified by human activity, mainly by converting native forest to agricultural use as arable land (70 percent) and pasture land (30 percent) (Meiyappan and Jain, 2012). These land-use changes can ultimately be attributed to population growth and increasing food demand, but this is not a simple relationship. Up to about 1950 the rate of conversion was higher than the rate of population growth, and occurred mainly in Asia, Europe, and North America. But latterly the global conversion rate slowed and most deforestation is now occurring in tropical America and Asia (FAO, 2012). Since 1960 global population has increased 2.3 times and food demand (calories consumed) 3-fold, yet the total agricultural land area has only expanded by 10 percent, with increased food production coming mostly from intensifying cropping and improved yields (FAO, 2011).

Thus, the pathways of land-use change are complex, and shaped by the interaction of various economic, political, technological, and sociological factors at different scales (Table 2). Today, large-scale forces, especially globalisation of commodity markets, have become the main determinants of land-use change, with certain national and local factors attenuating or amplifying their effects (Meyfroidt et al., 2013).

Table 2 Summary of current drivers of major land-use change

Driver of land-use change	Scale of driver		
	Global	National	Local
Economic	trade patterns commodity markets foreign investment diffusion of new technology	economic structures urban/industrialisation commodity prices agriculture incentives technology promotion	local market opportunities availability of labour access to capital technology adoption
Political	trade agreements environment and climate policies	land zoning/planning agro-economic and environment policies	land tenure and property rights local agro-policies
Social	international attitudes and values on environment consumption patterns	public attitudes and values on environment consumption patterns	individual and household behaviour consumption patterns

Global forces influence not only the land-use choices of millions of small producers but also those of large international investors. Driven by opportunities created by commodity markets, foreign investors are increasingly developing large-scale agricultural land projects in the less-developed countries. According to estimates of the Land Matrix[2], foreign investors have targeted at least 36 million hectares of land since 2000. The Tirana Declaration states that, where large-scale land deals occur without free, prior, and informed consent of present local land users, and without regard to potentially negative environmental impacts, they can be defined as acts of 'land grabbing'. Since a large proportion of large-scale land grabs entail preferential and/or unregulated access to freshwater, they have also been termed 'water grabbing' (Woodhouse, 2012).

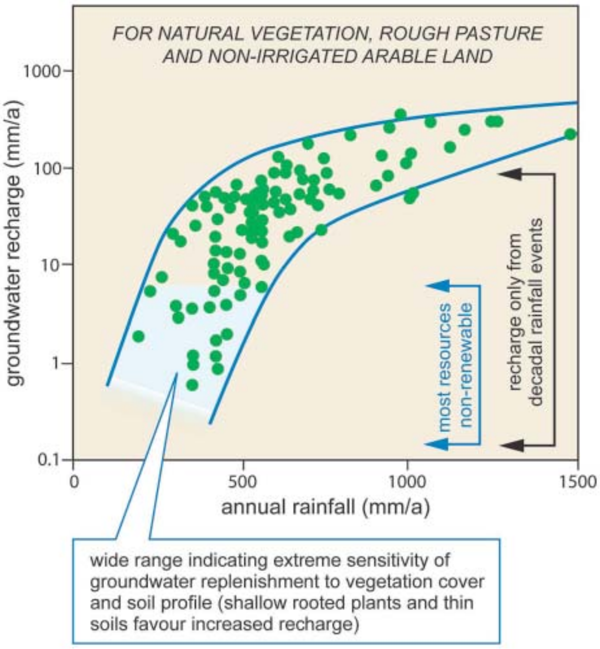
In the developing world, there is a pressing need to increase production of staple grains such as maize, rice, and wheat, whose yields are generally only 30–50 percent of those in more 'advanced' agricultural systems. Increased production will be sought through improving soil and water management practices. But concerns are growing about the impact on groundwater recharge, due to increasing consumptive water use, and nutrient and/or pesticide leaching.

[2] See also www.landmatrix.org

1.3 Land use and groundwater – an intimate relationship

Most groundwater originates directly from excess rainfall infiltrating the land surface. Thus land use has a major influence on both groundwater quality and recharge rates. Different land-use practices leave distinctive signatures on the quality of groundwater recharge and, in some instances, result in diffuse groundwater pollution, irrespective of climatic conditions. Similarly, land-use practices influence groundwater recharge rates, especially under more arid conditions (Figure 2).

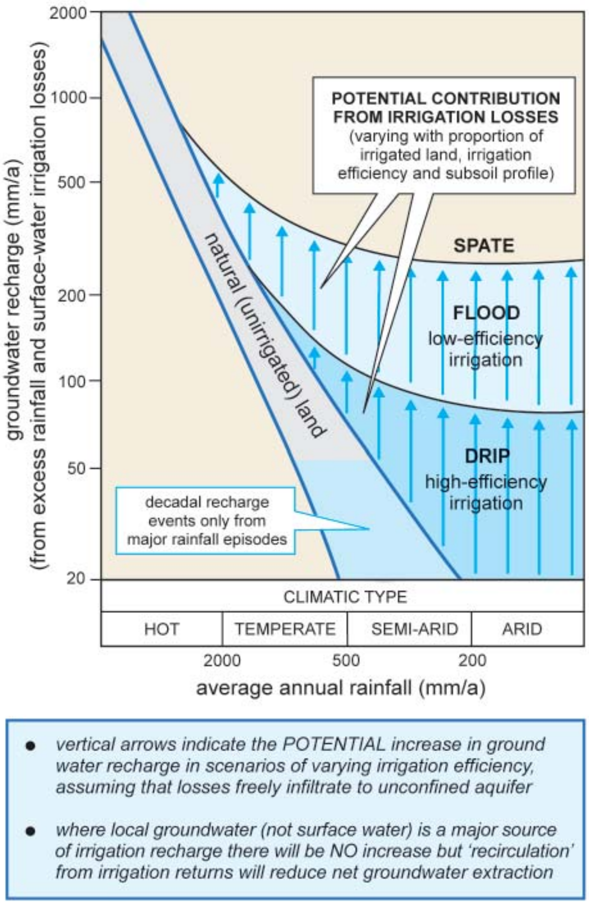
Figure 2 Influence of vegetation cover and soil profile on groundwater recharge rates (illustrated with data from Southern Africa)



Given the large storage capacity of most aquifer systems, groundwater response to land-use impacts will usually be gradual and often delayed. Moreover, groundwater quality degradation, once it has occurred, is likely to be long-lived and costly to remediate.

Amongst all types of major land-use change, extending irrigated agriculture using a surface-water source has the greatest influence on groundwater – both significantly increasing recharge and changing water quality as excess irrigation water infiltrates into shallow aquifers (Figure 3). Intensifying irrigated vegetable and fruit cultivation can have the opposite effect, since farmers tend to use 'precision irrigation', such as pressurised drip and micro-sprinkler systems, which can markedly decrease recharge rates (Garduño

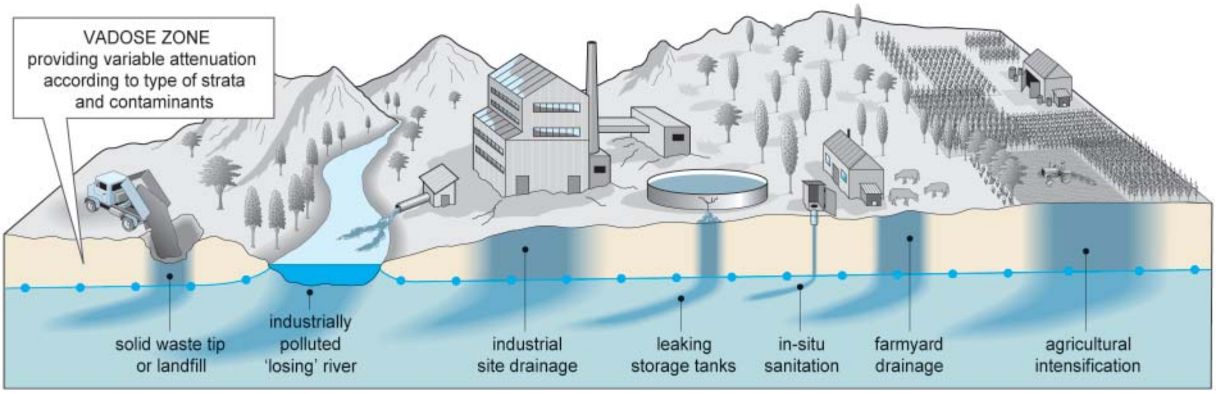
Figure 3 General relationship between groundwater recharge and annual rainfall and the potential increment from extensive surface-water irrigation



and Foster, 2010) and potentially reduce agrochemical leaching.

Groundwater pollution has a wide range of potential sources (Figure 4). It occurs when there is inadequate control over the subsurface contaminant load generated by man-made discharges or leachates, in relation to the attenuation capacity of underlying soils and strata (Foster et al., 2007). Some contaminants will be attenuated as a result of biochemical degradation and/or chemical reaction, and their sorption to minerals as water infiltrating through the sub-soil layers allows more time for contaminant attenuation processes. But not all sub-soil strata are equally effective in eliminating contaminants. Concerns about groundwater pollution relate mainly to shallow unconfined aquifers[3], especially where consolidated fissured rocks occur in the sub-soil strata. But a significant pollution hazard may also be present where aquifers are semi-confined, particularly when the overlying layer is relatively thin and permeable. The degree of attenuation will also vary widely with types of pollutant and polluting processes in any given environment.

Figure 4 Common activities generating a groundwater pollution hazard



In order to avoid groundwater pollution problems, selective land-use management policies and specific associated control measures need to be introduced to promote groundwater recharge quality protection at the local scale. Such policies and measures can provide major economic and ecological returns in the long run by preserving groundwater quality. It is also important to stress that some activities present a disproportionately large threat to groundwater. Thus spatially sharply focused and well-tuned pollution control measures can produce major benefits for a relatively modest cost.

1.4 Waterlogging and groundwater salinisation can be costly

Areas with a shallow water table are essential to sustain those aquatic ecosystems that depend upon groundwater discharge, although in some areas flow may be much reduced because of agricultural land drainage measures. Over more extensive areas the health of some natural terrestrial ecosystems will depend on deep-rooted trees and bushes being able to reach and tap the water table, at depths from 2 to 15m and

[3] An aquifer is said to be unconfined when it is open to direct climatic influences, with its water table generally close to the land surface. It is classified as confined when overlain by an impermeable layer, which prevents infiltration from above, and as semi-confined if the overlying layer allows some water to infiltrate from above.

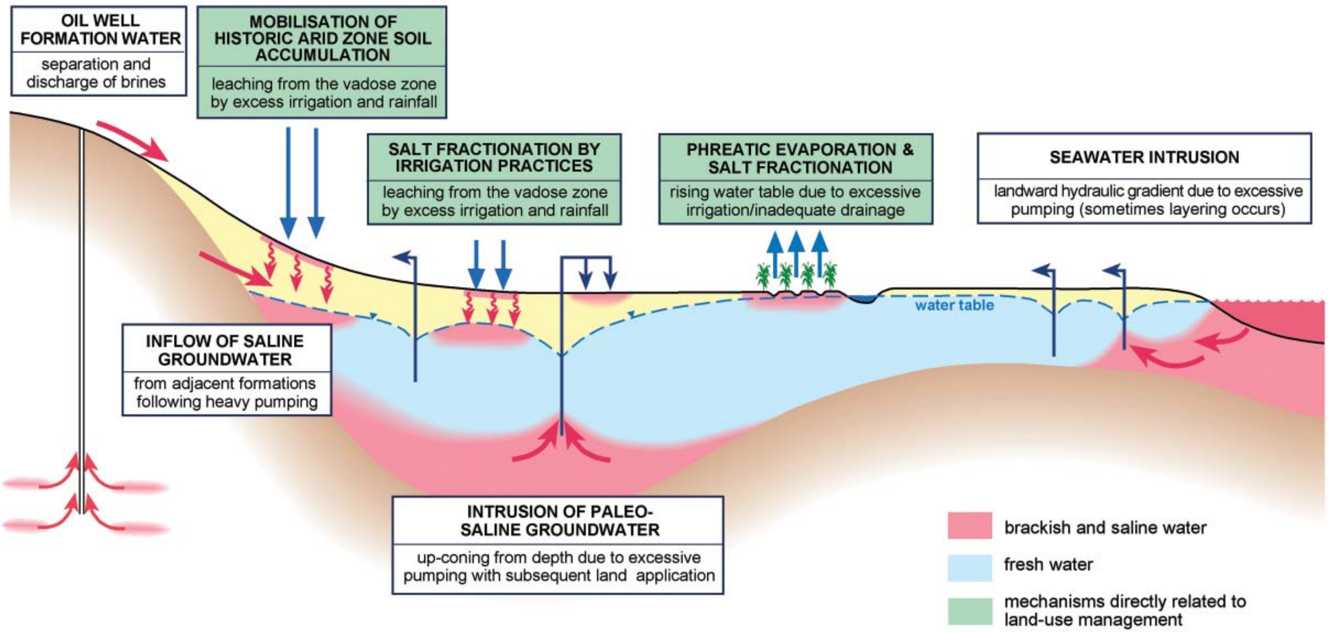
sometimes more. These are features of the natural landscape. Rising groundwater table is a related, but somewhat different, phenomenon which often has very negative impacts. It can arise from:

- land-use change – for example, introducing irrigated agriculture using surface water, which increases groundwater recharge rates (Figure 3), can lead to waterlogging and salinisation (Figure 5), with major reductions in crop productivity
- climate change – for example, major increases in frequency and intensity of exceptional rainfall events in groundwater recharge areas can result in water tables rising to levels higher than previous recorded maxima, causing extensive 'groundwater flooding' with damage to property and crops.

Both can be very costly because they often cause sharp reductions in agricultural land values and marked increases in property insurance costs. Mitigation will require improved management of irrigation water supply and/or major investment in land drainage measures.

Inadequate management of irrigation water can result in shallow salinisation of groundwater, through a number of different processes (Figure 5), which can have serious implications for all groundwater users and lead to soil degradation and land infertility. Globally 1.6 million ha of land are lost to salinity every year, offsetting much of the gain being made in agricultural productivity elsewhere. Many of the causes (indiscriminate aquifer pumping, seepage from canals and fields, and inadequate drainage) are groundwater related.

Figure 5 Origins of groundwater salinity and mechanisms of aquifer salinisation



2 How can land-use management incorporate groundwater?

2.1 Technical basis for groundwater-related land zoning

Applying special protection in specific zones, defined by hydrogeological criteria, provides better socio-economic and environmental returns than treating all land equally. There are different types of groundwater conservation and protection, which require the definition of land-surface zones at varying geographical scales (Table 3).

Table 3 Summary of groundwater-related land-management zones

Groundwater zone		Principal objective	Actions	Size (km^2)
Groundwater resource conservation		correct aquifer hydrological imbalance	promote demand and supply-side measures	50–100
Groundwater and soil salinisation control		halt saline groundwater intrusion and up-coning		5–50
		avoid pumping saline groundwater	strict limits on waterwell depth	50–100
		avoid rising water table and sub-soil strata salt leaching	control clearing of salt-tolerant vegetation	50–1000
Groundwater quality protection	Water-supply capture	safeguard groundwater quality in public supply	control land use/effluent discharge	5–50
	Aquifer recharge	protect groundwater quality in aquifer	potential pollution control by vulnerability	100–2000

GROUNDWATER RESOURCE CONSERVATION ZONES

Where groundwater resources are intensively developed, continuous aquifer depletion can occur with potentially irreversible side effects, such as saline intrusion, land subsidence, or aquatic ecosystem degradation. In such cases, a valuable management tool is to declare the affected area a 'groundwater conservation zone', within which constraints on new waterwell construction and/or requirements to reduce abstraction from existing waterwells are imposed. Such zones are usually delineated by groundwater flow analysis and numerical aquifer modelling, and are usually relatively small in area.

When a conservation zone is declared, the local water-resource agency should promote demand-side management through appropriate water-use efficiency improvements and water-use constraints amongst existing waterwell operators, and/or augment the supply side through promoting managed aquifer recharge where technically feasible (Box 1). For these measures to succeed, groundwater-use rights will need to be separate from land-use rights, with recognition that the former 'override' the latter.

Box 1 Augmenting groundwater replenishment

Aquifer recharge can be substantially modified by human activities. Hydrogeologists use the term managed aquifer recharge (MAR) to denote purposeful replenishment for subsequent recovery as water supply or environmental flow (Dillon et al., 2009). This can be achieved by using correctly maintained structures (such as infiltration wells, basins, and galleries) to inject water into subsurface storage. Possible sources include surplus river water, storm-water runoff from paved areas and tiled roofs, reclaimed wastewater, and seasonal public supply surpluses.

MAR should be distinguished from other human activities that can also augment replenishment such as unmanaged recharge – through deliberate disposal of wastewater in septic tank soakaways and via latrine seepage; and incidental recharge – occurring accidentally through excess agricultural and amenity irrigation, mains-water leakage, and seepage from sewers. While MAR measures are normally designed and maintained to achieve high unit recharge rates (50+ mm/d), the land areas used are usually much smaller than those involving 'incidental recharge'. Efforts are also required to harvest water resources through a wider range of land-management measures (e.g. Knoop et al., 2012).

One such example is *spate irrigation* – the traditional practice of diverting flood flows in ephemeral rivers and streams to spread water across substantial areas of adjacent agricultural land. This is most readily and successfully undertaken in mountain valleys and piedmont outwash plains, and has the multiple benefits of flood risk attenuation, soil moisture enhancement, and improving soil texture and fertility. In most conditions it also results in high rates of 'incidental recharge' to the underlying aquifer (Figure 3). A similar, smaller but more frequent, infiltration process is usually associated with *flood irrigation*. While such practices are favourable from a water-resource conservation standpoint, they may prove incompatible with modern, more intensive, cultivation techniques and be eliminated for this reason. Where this is the case, there will be an urgent need to explore MAR options as an alternative, in an attempt to restore this component of aquifer recharge.

A common consequence of declaring a 'groundwater conservation zone' is that the value of land with waterwell use-rights rises sharply compared to neighbouring land, often by a factor of 200–700 percent (Garrido et al., 2006; Garduño and Foster, 2010; Hombeck and Keskin, 2011). In this situation, the water-resource administration will need to resist considerable pressure for illegal waterwell drilling and corrupt use-right transactions.

GROUNDWATER SALINISATION CONTROL ZONES

Groundwater salinisation (Figure 5) is the result of various mechanisms, each requiring a different management response, including in some cases the declaration of 'groundwater salinisation control zones'. A range of measures will need to be taken:

- reducing abstraction and/or augmenting groundwater recharge to control saline groundwater intrusion or up-coning
- restricting waterwell depth to avoid accidentally pumping saline groundwater from depth for irrigation and then returning it to the freshwater aquifer by soil leaching
- managing the salinisation risk associated with introducing excessive surface-water irrigation in low-lying alluvial areas that can cause soil water-logging and salinisation
- clearing native vegetation in arid zones that can lead to the movement of salts that have accumulated over centuries in the sub-soils.

GROUNDWATER QUALITY PROTECTION ZONES

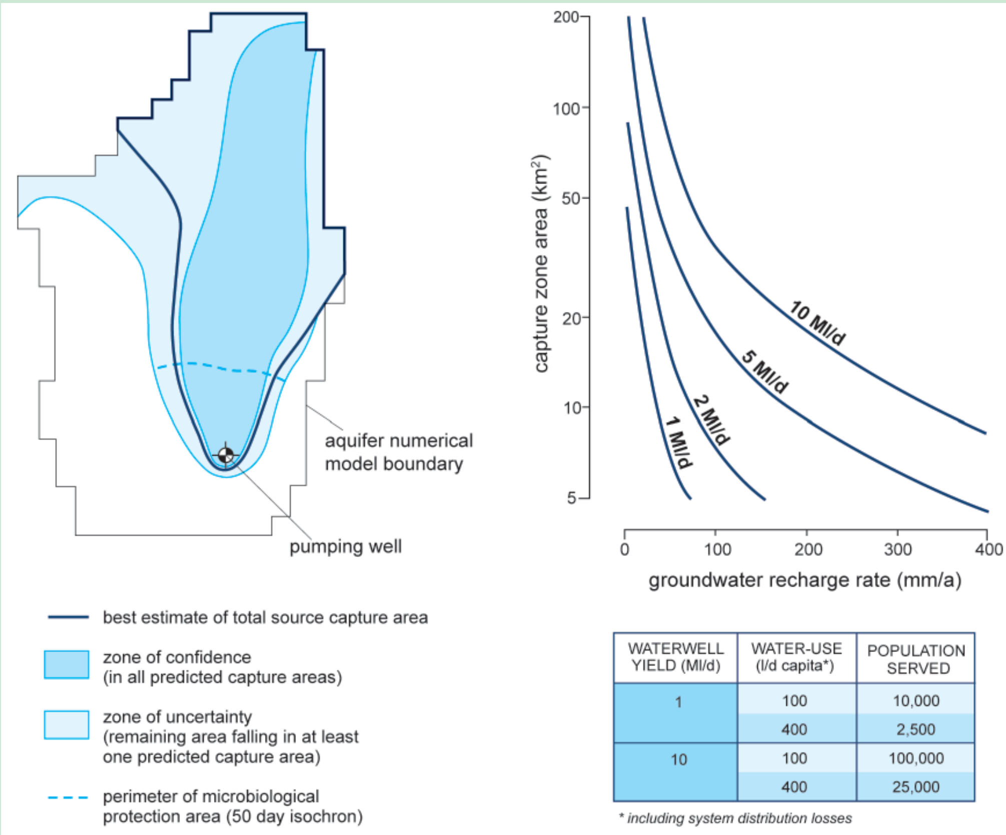
Groundwater quality protection zones play a useful role in setting priorities for land-use management, environmental audit of industrial premises, pollution control in the agricultural advisory system, groundwater quality monitoring, and public education more generally. All these activities are essential components of groundwater quality protection. A sensible balance needs to be struck between the protection of specific groundwater supply sources and the groundwater resources of aquifers as a whole (Box 2). While these approaches are complementary, the emphasis placed on one or the other will depend on the resource development situation and the prevailing hydrogeological conditions.

Box 2 Delineating groundwater quality protection zones

(A) Waterwell source (or wellhead) protection

This concept has been long established in some European Union countries. Special vigilance of groundwater destined for public supply involves protecting against both non-degradable pollutants (through capture-zone exclusion or flowpath dilution) and pollutants that decay with time (where residence time is the best measure). Subdivision of the capture zone is thus required (Foster et al., 2007), since in many cases it will be sufficient to apply severe land-use controls over just part (similar to so-called 'buffer strips' for surface-water protection), so as to ensure dilution of common pollutants that can be managed by the 'limit approach'. Water-supply capture zones can be best defined by aquifer numerical modelling (see Figure). The size, shape, and location of zone and sub-zone boundaries will be a function of various hydrogeological parameters, whose characterisation may be subject to significant uncertainty – thus sensitivity analysis (using statistical techniques) are used to establish a 'zone of confidence'. The capture-zone concept is simple and readily understood by land-use administrators needing to make difficult public decisions generated by groundwater protection policies. But in reality its application can encounter problems where the flow regime is unstable due to heavy seasonal pumping, where surface watercourses also receive aquifer discharge, where the groundwater divide is at a large distance, and in the case of karstic limestone aquifers with complex flow regimes. Public water-supply capture zones are thus best suited to uniform aquifers exploited by a limited number of large waterwells with stable pumping regimes.

Figure Typical form and area of waterwell capture zones in a simple groundwater flow regime



WATERWELL YIELD (Ml/d)	WATER-USE (l/d capita*)	POPULATION SERVED
1	100	10,000
	400	2,500
10	100	100,000
	400	25,000

* including system distribution losses

(B) Aquifer recharge protection

In some hydrogeological conditions the land area over which most recharge occurs can be precisely defined, with the groundwater in adjacent areas being more confined and naturally protected. Such areas are best characterised through 'aquifer pollution vulnerability' mapping to delineate 'recharge quality protection zones', where the importance for public water supply and/or aquatic ecosystems is justified (Foster et al., 2013b). The term 'aquifer pollution vulnerability' represents the sensitivity of an aquifer to being adversely affected by an imposed contaminant, consequent upon the natural characteristics of the strata separating the saturated aquifer from the land surface. To protect groundwater quality it will be necessary to constrain both existing and future land use, effluent discharge, and waste disposal practices. Instead of applying universal controls over land use and effluent discharge to the ground, it is more cost effective and less prejudicial to economic development to utilise information on aquifer pollution vulnerability when defining the level of control necessary to protect groundwater quality. Simple robust zones can be established on this basis, with matrices that indicate what activities are possible at an acceptable risk to groundwater (Foster et al., 2007).

2.2 Impediments to introducing land-use controls

Two main constraints must be overcome in order to integrate groundwater-based zones into land-use planning and decision-making.

LEGAL AND INSTITUTIONAL IMPEDIMENTS

In most countries, land and groundwater are governed independently, with separate use rights. This is sound practice from the standpoint of water-resource management, but problematic if the principal institutions involved – agriculture, water resources, environmental planning, municipal government, land-use administration, and water-service utilities – operate in separate 'silos' with ill-defined and poorly articulated linkages and interactions as regards groundwater. One example is the process of urbanisation, in which land-use issues are usually the domain of municipal government with no established mechanism for groundwater agencies to influence or veto decisions. Another example concerns major land transactions involving areas that exceed the political jurisdiction of local government. In such cases, investors may seek to circumvent local government and local land users, and deal directly with a national government ministry.

Institutional barriers will always exist and cannot be completely eliminated, since structural change often only rearranges them. It is thus essential to design institutional arrangements so that they nurture collaboration at institutional and stakeholder level.

ECONOMIC IMPEDIMENTS

The dynamics of groundwater flow systems are such that those often best placed to take action to augment, conserve, and protect groundwater may not be the principal beneficiaries of their actions, even though overall land-use potential will be enhanced by improving the availability and quality of groundwater.

Well-designed agro-environmental management or stewardship schemes with appropriate incentives can overcome this impediment. Nevertheless, landowners are still likely to raise objections about reduced land values or land productivity, and local authorities may tend to be more interested in allowing activities that increase rateable land value and thus augment disposable municipal income.

3 Which instruments facilitate coordinated governance?

Instruments that facilitate improved integration of land-use and groundwater governance fall into three categories:

- Policy and planning – national agriculture, water resource and environmental policy guidelines

- Regulatory – land-owner constraint through regulation or municipal decree, including local integrated water-resources plans, groundwater-use rights, aquifer management plans, and town-and-country planning statutes and procedures

- Participatory – land-owner participation through incentives, such as land purchasing and leasing agreements, agro-environmental management or stewardship schemes, and payments for ecosystem services.

The use of these tools will depend on the strengths and weaknesses of the prevailing political and legal framework, and on the threat to groundwater sustainability.

3.1 Policy basis for groundwater pollution control

CONSTRAINING DIFFUSE AGRICULTURAL POLLUTION

Diffuse groundwater pollution from agricultural land use cannot be controlled by local statutes and regulations. It requires clear 'national policy guidelines'. The principal components that need to be considered in drawing up policy include:

- best agricultural practice (BAP) guidelines that incorporate groundwater protection in order to avoid the worst excesses of agrochemical leaching

- pesticide registration procedures that include groundwater pollution risk assessment
- groundwater source capture and protection zone mapping for major public supplies, coupled with controlling farming intensity within the zones
- raising farmer awareness and supporting them in taking a balanced approach to agro-environmental management of their land.

Just adopting BAPs does not guarantee groundwater recharge quality that conforms to drinking-water guidelines and environmental quality standards, since BAPs alone are not sufficient to constrain agrochemical infiltration in soil profiles that are most vulnerable to leaching losses (Foster and Candela, 2008). Furthermore, natural aquifer denitrification can be an important mechanism in a few specific hydrogeological conditions, but should definitely not be assumed to be the norm.

In some cases, national policy should include retaining natural forest areas or promoting extensive agriculture in the broader interests of the environment. These policies have positive outcomes for groundwater conservation and protection. In such cases, the focus should be on critical groundwater recharge zones.

The European Union (EU) has accumulated over 60 years of valuable experience of agricultural intensification and controlling diffuse groundwater pollution. Early successful attempts to improve food-grain security and increase fresh fruit and vegetable production incidentally included much excessive and ill-timed agrochemical application. This generated heavy nutrient and pesticide leaching losses, which impacted groundwater quality. Today the environmental cost of excessive and/or ill-timed fertiliser and pesticide application is well recognised, and there is a more balanced policy of agricultural and environmental co-management of farmland. Specific EU legislation[4] aims to reduce agricultural impacts on the aquatic environment from both intensive arable cropping and intensive livestock rearing. Member States are obliged to define 'programmes of measures' to reduce agricultural emissions and achieve pre-defined water-quality goals (EC-Directorate General for the Environment, 2008). The Netherlands and Denmark, for example, have reduced nitrate leaching to groundwater from intensive livestock rearing by 50 percent over a 10–15 year period without a serious impact on productivity (Fraters and Foster, 2013).

ABATEMENT OF POINT-SOURCE POLLUTION

A set of underlying principles for controlling point-source pollution should be embraced in pollution abatement policy at national level. They are shaped by the 'fundamental social and economic rationales', summarised in Table 4, which should underpin the approach taken to abatement of groundwater pollution from industrial land use at the local level. Similar considerations apply to the control of potential point-source groundwater pollution from agricultural buildings and other non-industrial sources.

The threat from point-source groundwater pollution is generally greatest around major urban conurbations, industrial complexes, transportation hubs, and military installations. Failure to act systematically in its abatement will progressively reduce the long-term availability of high-quality groundwater in these strategic areas, as is witnessed by the extensive contaminated land (and groundwater) legacy from the 19th century in some industrialised nations. The persistence of various contaminants in groundwater, and the high cost and technical difficulty of their removal from groundwater, are critical considerations.

[4] Nitrates Directive 1991, Water Framework Directive 2000, and Groundwater Directive 2006.

Table 4 Principles underlying groundwater pollution control

Basic principle	Groundwater pollution control and quality protection context
Intergenerational equity	avoiding complacency about scenarios in which pollution incidents can take decades to impact deep groundwater supplies
Spatially differential controls	more economical to impose differential control spatially on potentially polluting activities (by aquifer vulnerability and local groundwater-use patterns) than to introduce universal regulations
Risk-based approach	given there are often significant error bands in predictions of contaminant flow direction and transport rate, protection efforts should always be prioritised on 'zones of confidence'
Precautionary principle	given significant uncertainty about the subsurface transport and attenuation of some water pollutants, 'worst-case' assumptions should be considered in elaboration of local policy
'Potential-polluter-pays' for protection	given the consequent difficulty in collecting unequivocal evidence of pollution incidents and their groundwater impacts, the 'polluter-pays-principle' must be interpreted this way for groundwater
'Prevent' or 'limit' philosophy	divide potential contaminants according to whether their acceptable concentration is effectively zero (and they must be 'prevented' from entering subsurface) or whether they can be tolerated up to a guideline value (and subsurface entry needs to be 'limited')

3.2 Regulatory options to control land-use change

STATUTORY GROUNDWATER AGENCY CONSULTATION

Statutory procedures can be established so that municipal or local government land-planning departments are legally required to consult groundwater agencies on all significant land-use changes, and to consider their concerns in decision-making. In some instances the groundwater agency can have the power of veto and should follow the principles in Table 4 in formulating their position. Major land-use developments should also be subject to an environmental impact assessment in which groundwater impacts are carefully assessed.

LOCAL LAND-USE PLANNING PROCESSES

Land-use planning zones and regulations, at local sub-catchment or aquifer level, can be very effective tools for groundwater resource conservation and quality protection, since they add scientific authority and clarity to the consultation process. Where groundwater recharge areas form distinct terrestrial or aquatic ecosystems, which remain sparsely populated and free from intensive agriculture, it may be feasible to incorporate them into national parks, where the special ecological protection will preserve groundwater.

Groundwater protection zones (Box 2) can readily be incorporated into local government land-use planning zones, with restrictions imposed to ensure acceptable land use. A good example comes from Barbados (Foster et al., 2007) where, as long ago as the 1970s, the strategic importance of groundwater led government to declare the following special waterwell protection zones based on estimated groundwater travel times to public groundwater sources:

- Zone 1 (300-day groundwater travel time): ban on housing and commercial development
- Zone 2 (600-day groundwater travel time): strict control on domestic/commercial wastewater and storm-water disposal arrangements and no fuel tanks allowed
- Zone 3 (5-year groundwater travel time): as above but special design of fuel tanks permitted
- Zone 4 (rest of island): domestic/commercial wastewater and fuel tanks permitted with normal design, but industrial wastewater subject to control.

Certain emerging threats to groundwater quality were not identified at the time of introducing the groundwater protection policy. These included displacing traditional extensive sugar-cane cultivation with much more intensive horticultural cropping involving higher fertiliser and pesticide applications, illegal disposal of industrial solid waste by fly tipping in abandoned limestone quarries, and illegal effluent disposal down disused waterwells. Measures were subsequently introduced to prevent or control these activities, and to improve the spatial coverage of groundwater quality monitoring.

3.3 Land-owner incentives for groundwater management

LAND PURCHASE AND LEASING AGREEMENTS

It should be possible for public water supply utilities or municipal water-supply service companies to compulsorily purchase significant parts of their groundwater source capture zones and then permit farming or recreational use under licence with specific controls (Box 2). The preferred land-use practices for capture zones are low-intensity pasture land, managed deciduous or coniferous woodland, or eco-farming with no pesticide use.

AGRO-ENVIRONMENTAL MANAGEMENT OR STEWARDSHIP SCHEMES

Such schemes use monetary or non-monetary incentives to encourage land owners or tenant farmers to carry out agreed agro-environmental management measures to preserve or enhance specific ecosystem services. These agreements can include measures to enhance the 'groundwater harvest', through selected cropping practices, ecosystem restoration, forest thinning, and removing alien tree species (Porras et al., 2013). Payment for ecosystem or watershed services (PES/PWS) are formal agreements with land owners to carry out agreed activities.

Agro-environmental management can be highly beneficial for improving the 'groundwater harvest' while simultaneously aiding climate-change adaptation by counteracting soil degradation, and climate-change mitigation through carbon capture. Formal PES and PWS schemes have been implemented in both industrialised and developing countries, and useful examples include the National PES Programme in Costa Rica and the Sloping Land Conversion Programme in China.

4 What is the future outlook?

This paper has raised important issues of land–groundwater and groundwater–land impact at a very wide range of spatial scales. To ignore groundwater considerations in land-use change decision-making, and land management more generally, will have a very high long-run cost, in terms of drinking-water security and aquatic ecosystem sustainability. Moreover, sharply focused land-use management measures can produce major groundwater benefits at relatively modest cost.

But one issue stands out above others. The escalating demand for food resulting from population and income growth will be met mainly by intensifying land use and, to a lesser extent, by further expanding the land under cultivation. This will inevitably put increasing pressure on groundwater resources in terms of both quality and quantity. Coordinated governance of land use and groundwater resources, and especially agricultural land management based on a coherent set of sustainability criteria aimed at enhancing both the food and groundwater harvest, will be crucial for future human development.

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