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# Irrigated Agriculture and Groundwater Quality - A Framework for Policy Development

Bonnie Colby Saliba, University of Arizona

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Water quality

Agriculture has been increasingly implicated in water quality deterioration, and linkages between soil erosion and surface water quality have received much recent attention. This article argues that irrigated agriculture's impact on groundwater is another water quality concern that is rapidly growing in importance and well deserves our profession's attention and research efforts. Groundwater is now the source of 50 percent of U.S. drinking water supplies and 40 percent of irrigation withdrawals, with reliance on groundwater varying tremendously across regions. Irrigated agriculture is the largest single user of the nation's groundwater resources, accounting for 70 percent of annual groundwater use. Groundwater withdrawals are increasing at double the rate of increase for surface water use, with half a million new wells drilled each year (Henderson et al., p. 9). As a part of a broader research effort examining water markets, values and quality in the western United States (Saliba, Bush and Martin), this paper explores the potential roles of public regulations and private markets in water quality management. The discussion focuses on nitrates, pesticides and dissolved solids — the three principal groundwater contaminants associated with irrigated agriculture.

## Irrigation and Groundwater Quality — What's the Connection?

Irrigated agriculture's potential impacts on groundwater quality stem from two facts — first, irrigation is the primary consumptive use of groundwater and second, large amounts of pesticides and fertilizers are applied to irrigated crop acreage. Factors that affect the rate and magnitude of agricultural groundwater contamination are summarized in Table 1. Management variables involve irrigation, pesticide, and fertilizer applications — though the impact of these practices on groundwater quality will vary greatly with the structure and depth of the material that lies between irrigated fields and the groundwater surface.

Table 1. Irrigated Agriculture and Groundwater Contamination

| Contaminant: | Nitrates | Total Dissolved Solids | Synthetic Organic Compounds |
|---|---|---|---|
| Agricultural Practices Which Affect Rate and Magnitude of Groundwater Contamination: | – quantity and timing of fertilizer applications relative to plant uptake<br>– form of nitrogen in the fertilzer<br>– quantity and timing of irrigations relative to fertilizer application | – quantity and timing of irrigations relative to plant uptake and leaching requirements<br>– type of irrigation system<br>– drainage systems and disposal of subsurface drainage water<br>– groundwater pumping rates | – quantity and timing of pesticide applications<br>– active ingredients in pesticides<br>– method of pesticide application<br>– quantity and timing of irrigations<br>– relative to pesticide application |
| Non-management Factors Which Affect Rate and Magnitude of Groundwater Contamination: | – climate<br>– permeability, porosity and layering within soil profile<br>– depth of vadose zone*<br>– occurence of denitrification which releases nitrates from soil into the air<br>(CAST) | – climate<br>– salinity of irrigation water*<br>– presence of saline water layers in aquifer<br>– aquifer vulnerability to saltwater intrusion (coastal areas)<br>– depth of vadose zone*<br>(FAO) | – climate<br>– depth of vadose zone*<br>– pesticide-specific factors affecting movement through soil<br>– soil characteristics, including hydraulic conductivity<br>(OTA, p. 284) |
| | Fertilizer | Irrigation Water | Pesticides |
| Magnitude of Applications: | 229 million acre-treatments, including 11.1 million tons of nitrogen.<br>(OTA, p. 284) | 169 million acre-feet of irrigation water applied to 50-60 million acres<br>(OTA, p. 283) | 280 million acre-treatments, 552 million pounds per year of active ingredients.<br>(OTA, p. 283) |

* Indicates variables influenced by human factors, though not solely by an individual farmer.

The material separating the land surface from the top of the groundwater table is the vadose (or unsaturated) zone, and is an important buffer between human activity and groundwater supplies. Substances which infiltrate below the crop root zone are transferred by water movement through unsaturated soil layers where varying degrees of degradation (decomposition of the pollutant) or adsorption (retardation of pollutant movement) can take place (Letey and Pratt). These processes substantially slow the rate of many contaminants' movement to groundwater and can prevent some substances (including many pesticides) from ever reaching the aquifer. However, other pollutants travel at the rate at which water moves through the vadose zone and can reach groundwater relatively quickly in irrigated areas. Nitrates and dissolved solids are in this category. Irrigation is a salt-concentrating process in regions where evaporation exceeds precipitation because salts remain behind in crops and the soil as evapo-transpiration occurs (CAST, p. 15). Concentration of total dissolved solids increases as water moves downward from the land surface toward groundwater. The assimilative capacity of the vadose zone is an important resource, but one which must be selectively managed within the limits of its ability to handle specific contaminants.

In some regions groundwater overdraft is accompanied by increased aquifer salinity. In coastal areas this occurs when salt water (heavier than fresh water) intrudes to replace groundwater withdrawn. In deep inland groundwater basins, connate water layers may lie under fresh water. Under conditions of rapid groundwater withdrawal this poor quality water can be drawn upward into active wells, causing well discharge to become saline. Upconing, as this process is called, may be avoided through careful determination of well depths and pumping rates (Bouwer). In so far as agriculture is a major groundwater user, it can contribute to water quality problems that accompany aquifer overdraft.

**Agricultural Groundwater Contamination — Extent and Impacts**

Information on the nature and magnitude of groundwater contamination is incomplete because aquifers not used for public drinking water are not routinely monitored. Organic hydrocarbons and inorganic chemicals in groundwater have been linked to pesticide and fertilizer application at various sites throughout the U.S. Nitrates from nitrogen fertilizer pose a groundwater contamination problem in several midwestern states, and the leaching of pesticides into groundwater has contaminated drinking water in the Northeast and forced well closings in the Central Valley of California (Henderson et al., OTA). When compared to contamination detected from landfills and other point sources, agriculturally-linked incidents have been small in number. However, some researchers warn that because agricultural chemicals are applied to vast areas of land, any contamination that does occur may be regional in nature and impractical to treat (CAST). In addition, groundwater and surface water are closely connected—groundwater supplies about thirty percent of U.S. stream flow. Thus groundwater contamination has the potential to affect surface water quality as well.

The consequences of groundwater pollution vary with the substances involved and the anticipated uses of the contaminated water source. In drinking water, nitrate concentrations greater than 45 mg/l may expose infants to methemoglobinemia (blue-baby disease). Older children and adults are not at hazard from this particular illness, though a few researchers believe that nitrates in drinking water can be linked to gastric cancer (Bouwer, p. 350-351). In irrigation water, excess nitrogen may delay harvest times and adversely affect yield and quality of citrus and other nitrogen-sensitive crops (FAO, p. 93). Total dissolved solids (TDS) lend a brackish taste to drinking water and the recommended maximum limit is 500 mg/l, though water of triple that concentration can be used when no better source is available. In irrigation water, TDS concentrations above 1000 mg/l cause yield declines for salt sensitive crops and around 3,000 mg/l even salt tolerant plants can exhibit significant yield declines (FAO). Dissolved solids can also contribute to clogging problems in drip irrigation systems (FAO). High concentrations of TDS are undesirable in water used for cooling and industrial processes to the extent that salts can accumulate on equipment, increasing operation and maintenance costs. The effects of detectable pesticide concentrations in drinking water are only partially understood and vary with the substances involved. Liver, kidney and central nervous system damage, birth defects, and cancers are potential hazards associated with chemicals found in pesticides (OTA, p. 32-33). However, no adverse health impacts from pesticides in groundwater used for drinking have been verified in areas where pesticide residues have exceeded health-advisory limits (CAST, p. 48). Little is known about the effects of pesticide concentration in groundwater used for irrigation, industry and other nondrinking water uses.

Existing documentation on the direct economic impacts of groundwater contamination focuses on costs of cleanup operations, switching to alternative water supplies and other site-specific actions. Difficulties in identifying costs include lack of information about the effect of agricultural practices on groundwater, the effect of groundwater quality changes on current and future water users, and the economic value of incremental declines in groundwater quality. If all agriculturally-linked incidents were combined and the time frame over which any effects might occur was considered, the costs could be significant. Any one incident may be important in the local economy in which it occurs, and the sum of site-specific costs could undervalue national impacts if widespread restrictions on water use had to be imposed (OTA, p. 38).

**Current Federal and State Policies**

While dozens of federal statutes define the federal government's authority and role in protecting water quality, few of these address agriculture's potential impacts on groundwater quality. The 1978 Federal Insecticide, Fungicide and Rodenticide Act gives EPA the authority to control and monitor pesticide sales, distribution, and use. EPA has established guidelines for disposing of pesticide storage and disposal and has established maximum contaminant levels for harmful substances in drinking water, including nitrates and some pesticides. Federal statutes assign federal agencies a lead role in developing scientific data, technical standards, and a regulatory framework, leaving program development and implementation responsibilities to the states. Few states have programs to prevent and reduce agricultural contamination of groundwater, though many states register and monitor agricultural chemical use. In general, an Office of Technology Assessment survey of state agencies with groundwater quality responsibilities found that states report less success in dealing effectively with agriculturally-linked contamination than with industrial and other point sources (OTA, p. 104). This may reflect lack of authority to regulate agricultural activities, inadequate agency budgets, and the inherent difficulties of dealing with nonpoint source pollution.

**Does Agricultural Contamination of Groundwater Require a Policy Response?**

Changes in water quality do not, by themselves, signal a need for corrective policies because technical quality indicators do not measure human values and impacts. If policies are predicated upon technical quality characteristics rather than the values and impacts associated with those characteristics, then scarce resources may be wasted solving "nonproblems" at high opportunity costs. Two important questions need to be addressed. First — are agriculturally-linked water quality declines a problem requiring a response? Second — if so, what is the most appropriate response?

Where agricultural contaminants are present in concentrations that impose human health risks, crop yield declines and other costs, interdependencies exist that may result in inefficient allocation of resources. Aside from externalities between current agricultural and non-agricultural water users, there could also be long-term and uncertain water quality effects imposed on future generations. One scientist has described the vadose zone as a "pollutant-filled time bomb which ticks slowly but which will eventually explode" (Goldschmid). This description reflects the fact that some substances move very slowly through the unsaturated zone and thus will not be detected in groundwater for decades (CAST, p. 14, 24). Much remains unknown regarding both the rate of contaminant transport through the vadose zone and the proportion of various pollutants that will eventually end up in groundwater. By the time contamination is detected it may already have moved extensively through an aquifer making corrective treatment difficult and expensive (CAST, p. 10). Institutional arrangements often give private water users no incentive to consider external effects of their water use on groundwater's suitability for other uses. Farmers currently have little reason to consider the water quality consequences of their activities, to adopt management practices and technologies with minimal water quality impacts, or to demand technological advances that meet agricultural production objectives while protecting water quality. Furthermore, in the absence of transferable water rights, water users have few incentives to coordinate their specific quality demands with available supplies of varying quality because rights to surface and groundwater sources have evolved based on historic use and other criteria having little to do with water quality. Under these conditions, groundwater contamination is more than a technical problem but also one of resource misallocation, unrevealed values concerning water quality, and distorted incentives related to water use.

**A Framework for Policy Development**

Ciriacy-Wantrup noted that water quality management presents an intriguing multiple use problem involving the sequence of different water uses over time, each with potential to change water's quality and thus its value for subsequent uses. Some important uses have minimal quality requirements — industrial cooling processes or waste disposal, while others — such as drinking water, must meet high standards. Lancaster argued that utility functions should be defined over attributes of consumption goods not merely over quantities of goods. This line of thought, focusing on the specific characteristics of goods and resources which make them productive and valuable, laid the foundation for hedonic valuation of non-market amenities. Lancaster's attributes approach is also extremely relevant to water policy. Water is a complex resource to manage because of its multiple attributes and interdependencies among potential uses. Various water users are concerned with different characteristics of water sources — navigability, salinity, rate of flow, bacteria levels, depth-to-lift and so on. Some water uses can be complementary (recreation and reservoir storage) while others decrease the suitability and availability of water for further use. Management of groundwater quality is hampered by lack of information regarding the social costs of contamination and the value of water quality improvements to various user groups.

Some central points become apparent regarding water quality policy. First, given that rates of groundwater pumping and overdraft can contribute to quality deterioration, groundwater use and quality must be managed in an integrated manner. Quality and quantity are not separable from a policy perspective. Second, close substitutes for native groundwater — including artificially recharged groundwater (Saliba), imported and native surface water, and effluent need to be considered in overall water quality planning. Third, more information regarding the willingness to pay for water of varying quality by user groups is needed to develop rational quality standards. Fourth, as the post-Coasian literature reminds us, an efficient solution to an externality need not focus on restriction or modification of the "emitters" activities. An efficient policy might require water users who demand higher water quality than exists given current agricultural practices to go elsewhere for water supplies, allowing some groundwater to receive agricultural contaminants and become limited in suitability for alternative uses. If several water sources are available to a region, there is no reason that the same standards should apply to all. Groundwater is used for many purposes other than drinking water, as is surface water. Differential protection policies can maintain high quality levels for uses that demand high quality while permitting limited degradation of other sources.

The broad economic problem centers on management of agricultural and other water-using activities to efficiently utilize available water resources — which will have different values in various uses depending on their quality. Water quality policy cannot effectively be separated from overall water allocation and supply management, including the institutional structures that govern water rights, transfers and values. The administrative and informational requirements of a comprehensive quality/quantity, surface water/groundwater (each of which may be native to the region or imported) central management scheme would be awesome. The next section explores the possibilities of a mixed public regulation/private market approach. The role of water markets in regional water allocation have been addressed elsewhere (Brown et al., Saliba, Bush and Martin) so this discussion will focus on water quality implications.

**Can Water Markets Contribute to Groundwater Quality Management?**

Market allocation involves many complexities springing from the nature of groundwater resources. These include stock versus flow components of groundwater, economies of scale in pumping and delivery, interdependencies in quality and availability among users of the same aquifer, interconnections between ground and surface water, and supply fluctuations across seasons and years. Anderson et al. have outlined a property rights system in groundwater that would facilitate market activity. Well-defined and transferable rights to both ground and surface water would enhance movement of water to high valued uses. Because quality affects the productivity and value of water to potential purchasers, well-functioning water markets could coordinate users' quality preferences with water sources having differing quality characteristics. A city, for example, may be willing to pay more for high quality groundwater than that water's marginal value product in agriculture, and could negotiate a transfer with farmers holding groundwater rights. In turn, farmers may be able to purchase and transfer effluent from municipalities at a lower cost than alternative water supplies. Saline water is limited in its potential uses and should sell at a lower price than fresh water — making it attractive to farmers growing salt tolerant crops and industries seeking cooling water. Such exchanges could (and do) occur in regions having several water sources of varying quality, a surface water delivery network connecting market actors, and aquifer hydrogeology conducive to transfer of pumping rights. These conditions are not uncommon where surface and groundwater supplies are being developed and actively managed.

Well-defined property rights are essential to efficient market allocation of goods and resources. In the case of water quality, buyers and sellers must have secure expectations regarding the quality characteristics of various water sources. A citrus farmer's willingness to pay for water rights would depend on his evaluation of present and future salinity levels in the water source to which he is seeking access, citrus being a salt sensitive crop. A municipality would also bid for water rights based on quality because salinity, bacteria count and other quality indicators affect treatment levels for drinking water. Policies designed to protect and maintain water quality at differing levels for various water sources could provide secure expectations and enhance market allocation.

One of the principal difficulties in setting water quality standards is lack of information regarding the value of incremental water quality differences to agriculture, municipalities and other water users. In a market setting, observed prices and economic behavior can give planners some indication of the relative value of water sources with varying quality characteristics. This information can be used to compare the costs of water quality regulations with the benefits of enhanced quality. Suppose households significantly increase bottled water pruchases following publicity regarding nitrates in the city water supply. It may be inferred that many consumers are willing to pay at least the cost of bottled water to avoid nitrates in drinking water. These inferential values can be compared to the costs of imposing fertilizer management restrictions on agriculture to determine which approach more efficiently resolves nitrate externalities — bottled water for households or regulation of farm practices. The distributional effects of these two alternatives on consumers and farmers vary greatly and would likely become the focal point of policy discussion. If it is true that infants under six months are the only persons harmed by nitrate concentrations exceeding federal standards, then only a small percent of households need to obtain alternative water supplies. On the other hand, there is evidence that farmers could benefit from the more precise fertilizer management needed to reduce groundwater contamination. Nitrogen and water application rates designed to match crop needs at various growth stages minimize groundwater contamination. Pollution potential of fertilizers is low up to the point of maximum crop yield in a yield response function but increases rapidly beyond that point. In the case of nitrates, efficient use of farm inputs and groundwater protection are complementary goals — though some farmers may find the increased management skills required outweigh perceived benefits.

Values inferred from market activity may be rough approximations of maximum willingness to pay but they are likely to be more helpful to water management agencies than no information at all. Market transfers, given a conducive institutional setting, can promote higher value uses of water, coordinate quality demands with available supplies, and provide information to water management agencies. In addition, persons holding water rights should have an added interest in protecting the quality of their water source, knowing that quality can affect its market value. However, this private incentive to protect groundwater will be insufficient to guarantee a specific level of aquifer quality because that is jointly determined by the activities of landowners overlying the groundwater basin. In a basin with substantial lateral movement, the benefits of one farmer's groundwater protection efforts will be shaped by his neighbors — a public good effect resulting in underprotection of the aquifer. Water quality regulations can supplement private incentives for groundwater protection, in addition to providing assurance to water market participants regarding the quality of various sources. Standards can also assure that some water sources remain at high quality levels, suitable for future demands that may not be reflected in today's water markets.

The lower Sevier river basin of southern Utah is one example of an active water market and allocation of water sources with differing quality characteristics. Principal market participants include several mutual irrigation companies, the Intermountain Power Project, municipalities, and individuals interested in water as an investment opportunity. Surface water is of poor quality in the lower river basin, containing 1,500 to over 3,000 parts per million of total dissolved solids. Surface water rights have been selling for $220 to $350 per acre foot in 1985 and are used primarily for irrigation. Municipalities and individuals interested in higher quality water are paying $700 to $1200 per acre foot for groundwater rights, which are transferable within designated zones. Groundwater rights have also been developed by irrigation companies in order to dilute saline surface water and allow a greater variety of crops to be grown successfully. The significant price differentials between ground and surface water rights provide indications of the relative value placed on high quality (and perhaps more reliably available) water by certain user groups, and a rationale for protection policies consistent with observed values of groundwater.

Price variations between water sources of different quality have also been observed in the South Platte River basin of Colorado and the Truckee-Carson basin in Nevada. In these areas groundwater is often the quality-limited source due to concentrations of copper, zinc, iron and other metals in excess of recommended limits (Saliba, Bush and Martin; Bouwer, p. 352). Though market transfers in Arizona are constrained by state water codes, inferential valuation techniques are being used to explore differences between willingness to pay for groundwater rights and substantially more saline Central Arizona Project water. While it will not be a simple matter to isolate the effects of water quality from all the other factors that determine water demand and prices, research on transactions involving water sources of varying quality can provide state agencies with some information on the value of water quality differentials.

## Summary and Conclusions

Agricultural groundwater contamination has been detected at specific sites throughout the U.S. While not widespread, many researchers believe both the number of incidents and the extent of their impact may grow as substances which have been applied in the last decade are slowly transported through the vadose zone and detected in groundwater. One of the chief difficulties with developing protective policies is lack of information on the value of water quality. In areas with water supplies of varying quality, water markets may provide indications of value. In addition, transferable water rights can coordinate user quality preferences with available water of varying quality. The opportunity to sell water rights could also provide agricultural and other water users with incentives to protect their water sources — incentives which need to be reinforced by regulation in order to assure a minimal level of water quality to market participants. A mixed private market/public regulation approach would permit some water sources to be degraded and limited to low quality uses, while maintaining others for current and future high quality uses. Observed market values, combined with inferential and contingent valuation of recreational and other non-market water uses, can help planners move toward efficient differential protection of water resources.

**Author's Affiliation:** Assistant Professor, Department of Agricultural Economics, University of Arizona.

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