The evolution of groundwater rights and groundwater management in New Mexico and the western United States

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Abstract Historically, rights in water originated as public property and only later became individualized rights to utilize the public resource, in a manner consistent with the public welfare needs of society, but protected by principles of property law. Five basic regulatory systems for rights in groundwater in the United States have evolved to date. The problems raised by the hydrologic differences between groundwater hydraulically connected to stream systems and groundwater in non-replenished aquifers have been resolved to some extent by a couple of leading court cases. Numerical modeling and other technical methodologies have also evolved to evaluate the scientific issues raised by the different hydrologic conditions, but these are not immune from criticism. The current role of aquifers is evolving into that of storage facilities for recycled water, and their utilization in this manner may be expanded even further in the future. The policy implications of the choices relating to joint management of ground and surface water cannot be overstated. As this paper demonstrates, proactive administration of future groundwater depletions that affect stream systems is essential to the ultimate ability to plan for exploitation, management and utilization of water resources in a rational way that coordinates present and future demand with the reality of scarcity of supply. The examples utilized in this paper demonstrate the need for capacity building, not just to develop good measurement techniques, or to train talented lawyers and judges to write good laws, but also for practical professional water managers to keep the process on a rational course, avoiding limitless exploitation of the resource as well as conservative protectionism that forever precludes its use.

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Résumé Historiquement, les droits d'eau étaient à l'origine un bien public; ils sont devenus plus tard des droits individualisés pour utiliser la ressource publique conformément aux besoins de salut public de la société, mais protégés par des principes de lois de propriété. Cinq systèmes de réglementation de base pour les droits sur les eaux souterraines aux États-Unis ont évolué jusqu'à aujourd'hui. Les problèmes posés par les différences hydrologiques entre les eaux souterraines hydrauliquement connectées aux cours d'eau et celles d'aquifères non réalimentés ont été résolus jusqu'à un certain point par quelques cas de jugement. La modélisation numérique et d'autres méthodologies techniques ont également évolué pour évaluer les résultats scientifiques apportés dans différentes conditions hydrologiques, mais ne sont pas à l'abri de critiques. Le rôle courant des aquifères évolue entre celui des possibilités de stockage pour l'eau recyclée et leur utilisation dans ce but peut être même étendue plus loin dans le futur. Les implications politiques des choix relatifs à la gestion simultanée des eaux souterraines et de surface ne doivent pas être exagérées. Comme le montre cet article, la gestion active de l'épuisement futur des nappes qui affecte les systèmes fluviaux est essentielle pour la capacité finale à planifier l'exploitation, la gestion et l'utilisation des ressources en eau d'une manière rationnelle qui coordonne la demande actuelle et future à la réalité de la rareté de l'alimentation. Les exemples utilisés dans cet article démontrent le besoin d'une capacité d'élaboration, non seulement pour développer de bonnes techniques de mesure, ou pour former d'excellents avocats et juges pour écrire de bonnes lois, mais aussi pour que des praticiens gestionnaires de l'eau maintiennent le processus dans un cours rationnel pour éviter une exploitation sans limite des ressources aussi bien qu'un protectionnisme conservateur qui empêche son usage à jamais.

Resumen Históricamente, los derechos del agua se originaron como un bien público que se transformaron después en derechos individualizados para usar los recursos públicos, de forma coherente con las necesidades de bienestar social, pero protegidos por los principios de la ley de propiedad. Hasta el momento, cinco sistemas

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reguladores básicos han evolucionado en los Estados Unidos de América en relación a los derechos en las aguas subterráneas. Los problemas surgidos por las diferencias hidrológicas entre las aguas subterráneas conectadas a corrientes superficiales y las aguas subterráneas en acuíferos sobreexplotados han sido resueltos hasta cierto punto por un par de casos judiciales notables. La modelación numérica y otras metodologías técnicas han evolucionado también para evaluar aspectos científicos asociados a diversas circunstancias hidrológicas, pero no son inmunes a las críticas. El papel actual de los acuíferos está evolucionando hacia el de instalaciones de almacenamiento de agua reciclada y su utilización de esta forma puede expandirse incluso más en el futuro. Las implicaciones políticas de las decisiones relativas a la gestión conjunta de las aguas superficiales y subterráneas no pueden ser exageradas. Como este artículo demuestra, una administración proactiva de las extracciones futuras de aguas subterráneas con efectos en los ecosistemas superficiales es esencial para la capacidad final de planificar la explotación, gestión y utilización de los recursos hídricos de forma racional, coordinando las demandas presentes y futuras con la realidad de la escasez de suministro. Los ejemplos empleados en este artículo demuestran la necesidad de construir capacidad y no únicamente de desarrollar buenas técnicas de medida, o la de educar reguladores y jueces de talento que redacten buenas leyes, pero también de gestores profesionales y aplicados del agua que mantengan el proceso en un compromiso entre evitar la explotación ilimitada del recurso y ejercer un proteccionismo conservador que impida su uso para siempre.

Keywords Groundwater management · Groundwater recharge/water budget · Groundwater/surface-water relations · Water-resources conservation · Water supply

Introduction

This paper begins by describing the importance of groundwater supplies to nations and states comprising the United States. It provides a brief description of the origins of property rights in surface and groundwater, and then addresses specifically the evolution of rules for allocating surface and groundwater within the United States. It concludes with a description of the four most common methods for allocation of groundwater—the rule of capture, reasonable use, the correlative rights doctrine, and finally, prior appropriation.

The hydrologic circumstances resulting from the extraction of groundwater and the effects on confined non-recharged aquifers, so-called “mined” underground water basins, as compared to aquifers hydraulically connected to stream systems, are explained. The two early, leading court cases addressing these two kinds of aquifers are discussed. A summary of the types of legal regulatory regimes and the issues of impairment of existing rights, social welfare costs and opportunities is provided.

Contemporary examples of how these issues are currently being addressed by regulatory agencies are set out in detail. This is followed by a discussion of the strengths and weaknesses of each approach.

The growing role of aquifers as reservoirs for storage of surplus or treated water is discussed in the final section of this paper. This section is followed by contemporary examples of how these programs have been successful and how utilization of aquifers in this fashion affects water quality within the aquifer.

Groundwater in the Western United States

Groundwater is an important source of water in the western United States, where the primary demand for fresh water is for irrigation, and the second largest demand is for domestic and commercial purposes (Western Water Policy Review Advisory Commission 1998). Groundwater contributes about a third of the water supply in the western United States. Infact, in many areas of the arid west, aquifers are the only source of water (id.). Many of the major aquifers in the west have already experienced significant groundwater level declines as a result of pumping, especially near large metropolitan areas (id.).

One factor contributing to the importance of groundwater is its availability both geographically and throughout the year. In much of the western United States, groundwater is available across much of the many basins. Surface water, on the other hand, is only available along a relatively few number of streams and rivers, as compared to the eastern United States. Consequently, the use of surface water away from the streams and rivers requires the fairly expensive construction of ditches or pipelines. Furthermore, because much of the surface water in the west originates as snowmelt in the mountains, the availability of surface water throughout the year can vary substantially. In summers and falls following winters with low snow packs, streams and rivers can often go completely dry.

Another factor contributing to the importance of groundwater is its quality. Almost all groundwater originates as rain or snowmelt that infiltrates through the soil into the underlying aquifers (Freeze and Cherry 1979). As a result, much of the groundwater in the western United States is relatively fresh despite the long residence time underground during which some minerals dissolve into the water. Much groundwater can be used without any treatment. Surface-water quality can be degraded via sediments and contamination by industrial and wastewater effluent discharges, irrigation return flows, and livestock waste, thereby requiring some treatment, e.g., chlorination and filtration, prior to use.

Finally, but perhaps most importantly, the growing population in the western United States will place an increasing demand on groundwater resources because many of the rivers are already fully appropriated and subject to drought. Groundwater reserves are savings accounts that can help supplement low surface water flows during droughts. The potential surface water shortages and increased groundwater demand are not limited to the western United States but extend also into Mexico, which shares surface and groundwater resources with the United States, for example, along the Rio Grande (Utton 1999).

Evolution of Water Rights in the Western United States

In the sense that form follows function, rights in water have evolved to ensure that societies' needs are met. Because water is a mobile resource, rules have been developed to regulate this mobility to preclude flooding, and to provide for dams that control its movement to make it available at times that society needs it the most. Because it is a critical part of capital production, laws have also evolved to ensure that it may be diverted and utilized and harnessed for irrigation, power generation, transportation and other uses. Because it is an essential element of life itself, laws have also evolved to ensure that its quality is protected and that minimal quantities are distributed to those who need it.

Historically, rights in water focused upon the power of the state to control it's use and distribution. Thus, for example, Roman Law ensured that rivers are property of the state, allocated for use by the state, and the rights of individuals to it were presumed not codified. Likewise, the early English common law struggled to fit water into the traditional format of real property law. This is to say, while recognizing the importance of property rights in individuals and promoting at least servient forms of capitalism, in post-feudal societies it was clear that water qua water was not considered a separate kind of property, but rather an extension of realty.

Early English cases spoke not in terms of what one could do with the resource as a matter of right, but rather what one could not do to others in the use of the right. The underlying principle of these cases was that each riparian proprietor has a right to use the stream as it passes his property, but no riparian proprietor has a right to use water to the injury of another (Gould and Grant 2000). This principle required that the stream be left substantially unchanged except for the minor effects of reasonable means of harnessing and using it as it passed (Gould and Grant 2000). Analogies to the law of trespass and easements played a much greater role than the law describing the nature of one's estate in the resource. While the right to ownership of land may have involved the coordinate rights of possession, utilization, ownership, inheritance and sale, no such concepts applied to water.

These same principles were adapted to early decisions in the eastern United States. Surface water sources were abundant, stream flow was contingent upon rainfall through short reaches of streams, competition for use was minimal, and most other laws followed those of England, having little other historical antecedents. As a result, the riparian doctrine took root and simply established the principle that those adjoining a stream system had a right to reasonably use their water on the related land, so as not to interfere with the use of another. Such rights did not contemplate ownership but rather participatory responsibility in the use of a common resource.

The form of water law and concomitant rights in water in the western United States did not follow the precepts in the eastern part of the country. Rivers provided extraordinarily variable flow and traversed vast areas of public lands where no land in private ownership graced their banks. Their highest economic use was typically outside the banks of the stream for agriculture, and the obligation for certainty of right was driven by the need to promote capital investment.

Thus, rights in water were developed in the western United States around the resource water, not the resource land to which water was appurtenant. Finally, to ensure that capital investment was adequately served, there needed to be a system to allocate water definitely and finally in times of shortage. The system devised was that of prior appropriation—the system by which the most senior person to establish a use of the right got that right served in times of shortage.

The constitutions in virtually every western state established the principles that beneficial use creates a usufructory property right in the resource and that beneficial use is the basis of the right, meaning that the right only exists if it is actually being put to use. It is the measure of the right, meaning that the right is only as great as the amount actually used beneficially and not wasted, and finally it is the limit of the right, meaning that if a party fails to beneficially use it, it reverts to the state for use by another.

Early Legal Regimes for Groundwater Management

While rules for the utilization of surface water developed through constitutions, statutes and case law, groundwater was not so thoroughly regulated. This was due in part to a lack of hydrologic knowledge as to the nature of its occurrence, with many experts believing that it flowed in vast underground streams. Also, the principle of ownership of land, so vital a part of the United States heritage, played a role. One was thought to own from the center of the earth to the highest vertical point in the heavens, all of the minerals and riches above and beneath one's land. In some states, such as Texas, a rule of "capture" of groundwater became the law.

The rule of "capture" holds that any person holds the right to divert until there is a complete depletion of all of the waters underlying their land. The only limit on this rule is that one cannot divert water in a way that maliciously causes injury to another. The English or common-law rule is that "the person who owns the surface may dig therein, and apply all that is there found to his own purposes at his free will and pleasure; and if, in the exercise of such right, he intercepts or drains off the water collected from underground springs in his neighbor's well, this inconvenience to his neighbor falls within the description of *damnum absque injuria*, which cannot become the ground of an action". The landowner may sell or grant his right to withdraw the water to others (Gould and Grant 2000).

A second rule, a sort of vertical riparianism, is the rule of reasonable use. Under the rule of reasonable use, one can divert any amount of water reasonably necessary to make use of his overlying land. One cannot divert water to another location, but so long as it is utilized on the overlying land and the use is reasonable, the depletion is allowed. As stated in Corpus Juris Secundum (1998), "In some states, the rule of the common law followed in early decisions has given way to the doctrine of reasonable use limiting the right of a landowner to percolating water in his land to such an amount of water as may be necessary for some useful or beneficial purpose in connection with the land from which it is taken, not restricting his right to use the water for any useful purpose on his own land, and not restricting his right to use it elsewhere in the absence of proof of injury to adjoining landowners".

A third system is the correlative rights doctrine. Under this system, aquifers are divided by the share of overlying land above the aquifer. Each surface owner is entitled to utilize his share in proportion to the overlying land owned by him. "Under the rule of correlative rights, the rights of all landowners over a common basin, saturated strata, or underground reservoir are coequal or correlative, and one cannot extract more than his share of the water, even for use on his own land, where others' rights are injured thereby" (Corpus Juris Secundum).

A fourth system is the law of prior appropriation, under which parties are entitled to drill wells and deplete water for use at any location selected by them, so long as they do not cause injury to a prior appropriator who has previously drilled a well and is placing it to beneficial use.

A fifth system, not formally adopted in any state, but interesting because its elements form the basis of water rights administration in many states, is embodied in the law of torts. The law of torts defines those circumstances in which one party breaches a duty to another with respect to that other person's property or person. When such a breach occurs, then the courts will award damages to the prevailing party. *The Restatement of the Law, second, Torts* (1965–79) is a compilation of commentators' views as to the extent of duty owed by one to another, and under what circumstances damages can be awarded. Unlike the correlative rights doctrine that addresses injury to others only when a person uses more than their proportional share of water, the Restatement addresses the issue of invasion of another's rights in groundwater and concludes that no party can drill a well that causes unreasonable harm to another, and notes that unreasonable harm is determined by the extent of injury to expectation of use by the person with an existing well, when one drills a new well and diverts water.

The Restatement of the Law, second, Torts § 858, Liability for Use of Ground Water, states that:

1. A proprietor of land or his grantee who withdraws groundwater from the land and uses it for a beneficial purpose is not subject to liability for interference with the use of water by another, unless
   - Clause a, the withdrawal of groundwater unreasonably causes harm to a proprietor of neighboring land through lowering the water table or reducing artesian pressure,
   - Clause b, the withdrawal of groundwater exceeds the proprietor's reasonable share of the annual supply or total store of groundwater, or
   - Clause c, the withdrawal of the groundwater has a direct and substantial effect upon a watercourse or lake and unreasonably causes harm to a person entitled to the use of its water.

2. The determination of liability under clauses a, b and c of Subsection 1 is governed by the principles stated in §§ 850 to 857.

The official comment to section 858 provides useful explication. A "grantee" is one to whom a proprietor has assigned the right to extract groundwater; the grantee need not acquire the overlying land. Clause 1a protects owners of small wells using water on overlying land against harm from large municipal or industrial wells supplying water to non-overlying lands (making it, in this respect, like the common law reasonable use doctrine). Clause 1a also extends protection to owners of small wells against harm from unreasonably large wells supplying water for use on overlying lands (making it, in this respect, unlike the common law reasonable use doctrine). Subsection 2, by referencing §§ 850–857, incorporates the reasonableness concept of riparian law for surface waters (Gould and Grant 2000).

None of these regimes is perfect. The rule of capture suffers from the twin flaws of destroying any legitimate expectation of use of a well, if another can make it useless, and it encourages a race to the bottom of the aquifer. The reasonable use rule leaves it to the courts to determine what use is reasonable and needlessly ties the use of water to the overlying land, when use elsewhere might provide greater benefits to society.

The correlative rights doctrine artificially ties surface ownership to groundwater ownership, when the goal of society is to place such water to the highest economic or social use, in the best possible place. It ties investment in what may be useless land to ownership of a precious resource that happens to lie under the land.

The prior-appropriation doctrine gives the benefit of protection of capital investment in wells and water projects, but leaves unanswered the question of whether a particularly low efficient use of groundwater, established one week before a very efficient one is sought, should carry the day.

The Restatement, while interesting and capable of allocating costs and benefits through damages, leaves the definition of highest and best use to the courts, which are not necessarily properly suited to the task.

Basic Hydrology and Issues in the Western United States

Technical issues in groundwater management in the western United States vary according to whether the groundwater occurs in mined basins or basins hydraulically connected to rivers. While they occur in both types of basin, water level declines caused by pumping are managed differently in each type of basin. The time-lag problem of stream depletion is relevant primarily only in basins hydraulically connected to rivers.

A mined basin may be characterized as a closed system, i.e., a finite volume of water that is not replenished by an outside source. Mined basins are those basins that have very little natural recharge and, like mining a mineral deposit, any removal of the resource reduces the total amount available in the future. While a mined basin may contain, and be hydraulically connected to, perennial streams or springs, most of the surface water courses are ephemeral and provide little recharge to the basin relative to the magnitude of groundwater withdrawal. Consequently, the amount of water in a mined basin decreases in approximately direct proportion to the amount of water pumped from wells.

Basins hydraulically connected to rivers differ from mined basins primarily by the presence of a stream system or river that is capable of recharging groundwater to such an extent that water level declines caused by pumping are minimized or even eliminated. Although the volume of the aquifer in a basin hydraulically connected to rivers is finite, withdrawal of groundwater by pumping is compensated in whole or in part by surface water recharge. The surface water is an outside source of water, either from snowmelt or rain in mountains along the basin periphery or via a stream or river from another, upstream basin. Groundwater pumping in a basin hydraulically connected to rivers can be considered analogous to taking water out of a bathtub with the faucet running whereas pumping in a mined basin is taking water out of a bathtub with the faucet turned off. The decrease in the amount of groundwater in a basin hydraulically connected to rivers depends not only on the rate of groundwater pumping but also on the rate of surface water recharge. Similarly, the rate of surface water flow through and out of the basin (bathtub overflow) also depends on the relative magnitudes of groundwater pumping and surface water recharge.

A cone of depression refers to the drawdown of the water table, or potentiometric surface, caused by a pumping well. Generally, the drawdown is deepest nearest the pumping well and decreases radially away from the well (Freeze and Cherry 1979). As pumping continues, the cone of depression becomes deeper and extends farther away from the well, somewhat like the depression around a straw in a thick milkshake.

Groundwater administrators in both mined basins and in basins hydraulically connected to rivers evaluate applications to appropriate water by estimating the extent of the cone of depression likely to result from the proposed groundwater withdrawal. Administrators do so to avoid well impairment, the interference with the rights of others who have existing wells. They can estimate the dimensions and rate of propagation of a cone of depression using the Theis (1935) solution, discussed below. Well impairment may occur when a new groundwater appropriation lowers the groundwater to a level near or below the bottom of existing wells. Thus, even though there may be sufficient water available for both users, the new user effectively diminishes, or eliminates altogether, the ability of the previous user's well to withdraw groundwater. Well impairment is usually controlled by relatively local factors such as the distance between the new well and existing wells, the rate of groundwater withdrawal from the new well, the hydraulic properties of the aquifer between the new and existing wells, and the age and depth of the existing wells (DuMars 1996).

In addition to impacting nearby wells, an expanding cone of depression can also impact nearby streams and rivers. As the cone of depression expands toward a stream, it lowers the water table adjacent to the stream and either decreases the amount of groundwater discharging to the stream or increases the amount of water the stream loses to the aquifer. In either case, groundwater pumping decreases the amount of water in the stream. However, the impact of groundwater pumping on a nearby stream is not instantaneous. There is a time lag from when the pumping starts to when the pumping begins to deplete the stream. In addition, there is a time lag from when the pumping ends to when stream depletion ends. This time lag presents potential problems in conjunctive management of surface and groundwater resources. Calculation of stream depletion and administrative methods for managing groundwater pumping to prevent stream depletion are discussed below.

Case Law on Groundwater Management in Mined Basins and Basins Hydraulically Connected to Rivers

Interestingly, two of the earliest decisions regarding management of extraction of groundwater came from the state of New Mexico. It is probable that these actions arose because of the diverse geography of the state. The state is bisected by a major river running from north to south, the Rio Grande, which begins in the snow-packed mountains of Colorado and drops into the large alluvial valleys in the central part of the state, eventually winding up at the border between Mexico and the state of Texas near El Paso.

The river water is allocated among the states of Colorado, New Mexico and Texas by an interstate compact, and between the United States and Mexico by virtue of an international treaty. The net result is that certain quantities must arrive in the Rio Grande river channel near El Paso, Texas every year to meet these national and international demands. En route to the south, the river traverses the city of Albuquerque, where groundwater is pumped to supply the city's domestic water needs. The aquifer from which Albuquerque obtains its water is hydraulically connected to the Rio Grande. Furthermore, all rights to the use of surface water from the river in New Mexico have been established for many years. The state of New Mexico follows the law of prior appropriation, and any junior well that would draw water from a senior right in the river would be inconsistent with that doctrine.

The State Engineer of New Mexico was faced with the task of allowing Albuquerque's pumping of the groundwater through junior wells to meet the municipal demand, while at the same time protecting the rights of senior surface water users and ensuring sufficient amounts of water arrived at the downstream parts of the system to meet the national and international obligations.

To accomplish this result, the State Engineer declared the basin adjacent to the river to be under his jurisdiction. Having done so, the city of Albuquerque was obligated to apply to the Engineer for a permit to drill new wells. The city was reluctant to do so, and upon application declared that the State Engineer had no authority to regulate their pumping. They argued inter alia that the ground and surface water regimes were each regulated by their own set of statutes and therefore, as a matter of law, control of the surface water could in no way limit their right to unlimited pumping of the groundwater that was hydraulically connected to the river.

The State Engineer granted their permit to pump up to the capacity of their wells, but conditioned their permits on the city's obligation to contact surface right holders on the river and "retire" from use the exact amount of surface water consumption that would occur in the future as a result of pumping the wells. The city of Albuquerque appealed this condition, but the New Mexico Supreme Court upheld the State Engineer, thus establishing a principle of coordinated groundwater and surface water management not recognized elsewhere in the United States (*Albuquerque vs. Reynolds* 1963). As discussed more fully below, variations of this system have been adopted with varying degrees of success in other states.

The second leading case arose in the eastern part of New Mexico where a completely different hydrologic condition prevails. Most of eastern New Mexico overlies the westernmost reach of the Ogalalla aquifer. This vast aquifer lies under the so-called breadbasket of the United States. In New Mexico, however, unlike areas farther east, the aquifer is shallow and has no surface recharge other than rainfall.

The State Engineer was faced with a circumstance whereby wells were being drilled into the aquifer without regulation and groundwater was being mined at an alarming rate. To regulate this extraction in a prior-appropriation state created a policy problem of extensive proportions. The State Engineer adopted a system that combined the doctrine of correlative rights with that of the prior-appropriation doctrine.

The system divided the land overlying the aquifer into sections of equal size. It then, in theory, calculated the amount of groundwater in storage under each surface water unit. It then established a permissible rate of allowable water level drawdown or extraction that would be suitable to the state from a policy perspective. The rate was determined to be the amount of decline in each square by wells that would ensure that at the end of 40 years there would be one third of the water remaining in the aquifer for users at that time. The rate also considered the proximate distance that farmers could lift water economically, and anticipated that at the end of the 40-year time period (the anticipated time it would take to fully depreciate farm capital) farmers could no longer farm in any event.

After the adoption of these criteria, an oil company applied to drill a well within a designated hydrologic unit of the basin. The hydrology showed that if the well were allowed to pump it would lower the water table in a senior well owned by an agricultural user. The senior user argued that allowing the well would violate the doctrine of prior appropriation because his well, being there first, could not be adversely affected by a junior user.

The State Engineer considered the application and indicated the relevant question was not whether the well would lower the water table in the senior well, but whether it would lower it at a rate faster than allowed under the "mining" criteria established by his office. The State Engineer concluded that the rate of drawdown was within the amount allowed by his criteria and granted the application.

The farmer appealed, and the New Mexico Supreme Court held that the State Engineer was within his power to permit mining of aquifers without running afoul of the prior-appropriation doctrine (*Mathers vs. Texaco* 1966). This was true, concluded the court, because every new application in a mined aquifer caused the water table to decline. Certainly a person who put down a 10-foot well could not argue that he had appropriated an entire aquifer because any new well would lower the water column in his existing well. Thus, the doctrine of prior appropriation was forced to yield to pragmatism and economics. The system is one of correlative rights, because if one is in a block or sector that has not yet reached the full, allowed rate of decline, one can drill a well, irrespective of the fact that it may cause some drawdown on others. Conversely, it honors priorities, because once all of the space in the block is taken, no junior well can increase the rate of decline beyond that permitted by the system.

These two cases from New Mexico generally illustrate the application of conjunctive use and prior appropriation in groundwater management in the western United States. However, there is a wide array of groundwater management techniques that vary from state to state, many of which share the common goal of coordinating the "use of ground and surface waters in order to get the maximum economic benefits from both resources" (Johnson and DuMars 1989; Glennon and Maddock 1997).

Summary of Problems in Mined Basins and Basins Hydraulically Connected to Rivers

In summary, two different but related problems arise in the two different kinds of basins. In the hydraulically connected basin, a well applicant must demonstrate that (1) his well will not cause injury to senior wells in the immediate area so as to make them unusable, i.e., it will not unreasonably interfere with those senior wells (the "well interference problem"), and (2) he must show that he has accounted for the water taken from the stream so that there is no new appropriation of surface water. This is called the "groundwater/surface-water equilibrium" problem. This can be accomplished either by retirement of rights on the stream or importation of new water into the stream.

In the mined basin, there is also the problem of well interference, but typically this occurs because of simple well proximity such that the proximate cones of depression of the two wells interfere with one another. This problem is solved by well spacing. The more complicated issue is determining the proper allowable rate of drawdown within the basin. This is, of course, a policy choice of tremendous proportions. The issue is sometimes defined in terms of "safe yield" of the aquifer. The question as to what is "safe yield" often is answered with a tautology, such as that a safe yield is extraction of groundwater that can be allowed in a manner that does not cause unreasonable consequences, meaning, of course, that a safe yield is one that is not unsafe. It is not the purpose of this paper to clearly define "safe yield", but rather to indicate that this cryptic definition is at the heart of water law in all mined aquifers. The following table reflects some of the variables that might go into the calculus of these policy issues.

Table 1 Typical variables considered in addressing aquifer withdrawals

Variable	Mined aquifers	Aquifers hydraulically connected to rivers
Policy/technical issues		
Drawdown rate	Always	Seldom/well interference
Stream depletion rate	Never	Always
Subsidence	Always	Seldom
Water quality degradation	Always	Seldom
Third-party impacts		
Environmental	Seldom	Always
Economic	Always	Always
Planning horizons	Always	Always/lag effects
Distributional issues		
Water Markets	Seldom	Always
Banking	Never	Seldom
Conservation	Always	Always

Whether these variables are considered when making policy choices depends on the physical characteristics of the aquifer. For example, stream depletion rate is always considered for aquifers hydraulically connected to rivers because groundwater pumping could injure prior appropriators of surface water. Mined basins, on the other hand, do not have significant streams that would be depleted by groundwater pumping.

Contemporary Examples of Regulation and Problems

Administration and regulation of groundwater pumping has evolved with the development of mathematical techniques and computer modeling. Early administration relied on qualitative analysis, discussed below, of the effects of groundwater pumping on stream depletion. Later, with the development of analytical solutions for drawdown and stream depletion, groundwater regulation took a quantitative, but very conservative approach. These analytical solutions generally described only one hydrologic process in a uniform, homogeneous aquifer. Most recently, with the advent of more sophisticated computer models, administrators are better able to simulate several hydrologic processes and aquifer heterogeneity. Nevertheless, administrators in different states take vastly different positions on whether applications to appropriate groundwater should be approved (Glennon and Maddock 1997).

Darcy's Law, based on a laboratory experiment published in 1856, is the earliest and perhaps most fundamental principle in groundwater hydrology (Freeze and Cherry 1979). Generally stated, Darcy's Law says that the rate and direction of groundwater flow are proportional to and determined by the hydraulic gradient. The New Mexico State Engineer used Darcy's Law qualitatively to administer groundwater pumping in the Albuquerque Basin. Hydraulic gradient data indicated that groundwater in the Albuquerque Basin moved toward and discharged to the fully appropriated Rio Grande. The State Engineer concluded that groundwater withdrawals would reduce the discharge to the Rio Grande, which in turn would reduce the surface water supply. Consequently, the State Engineer denied the City of Albuquerque's 1957 applications to appropriate groundwater (OSE 1957).

In 1935, C.V. Theis published an analytical solution for predicting water level declines, or drawdown, in an aquifer due to a pumping well at any distance from the well and at any time after groundwater pumping has started (Theis 1935). The calculation provides only an estimate of drawdown, as the Theis solution incorporates some assumptions that are not met in any aquifers, such as constant thickness, infinite extent, and uniform hydraulic properties. Nevertheless, the Theis solution provides useful predictions of drawdown at nearby wells and is currently used by the New Mexico State Engineer to evaluate the potential for well impairment. The State Engineer uses more sophisticated, numerical models to evaluate the potential for well impairment only in those few basins deemed to have adequate data on hydraulic properties.

In 1941, Theis developed a solution to predict the effect of pumping a well on the flow of a nearby stream (Theis 1941). Theis' 1941 stream depletion solution indicates that groundwater pumping can deplete the flow in a nearby stream and, with continued pumping, the stream depletion approaches the groundwater pumping rate. Theis' 1941 solution provides only an estimate of stream depletion because it is based upon and incorporates the same assumptions as his 1935 drawdown solution. The New Mexico State Engineer used Theis' 1941 stream depletion solution, in addition to the qualitative evaluation mentioned above, to evaluate Albuquerque's 1957 applications. The State Engineer denied the applications because return flow credits would not cover the river depletion that would be caused by the proposed pumping, and the City of Albuquerque refused to retire surface water rights to make up the difference. The denial led to the case *Albuquerque vs. Reynolds* (1963).

The New Mexico State Engineer now uses the Glover-Balmer formula to evaluate stream depletion (Glover and Balmer 1954). The Glover-Balmer solution is equivalent to Theis' 1941 solution and provides an estimate of stream depletion because it incorporates the same assumptions as Theis' solution. Like the Theis solution, the Glover-Balmer solution predicts that with continued pumping, the river will supply all of the water pumped from the well. The degree to which the Glover-Balmer calculation overestimates river depletion depends on the net effect of the differences between the actual conditions in the aquifer and the assumptions incorporated by the theoretical formula (Sophocleous et al. 1995). The most important differences between the assumptions and actual aquifer conditions are the hydraulic connection between the river and the aquifer, the degree of river penetration into the aquifer, and aquifer heterogeneity. Numerical models can, to some extent, incorporate these factors.

The New Mexico State Engineer is now beginning to use numerical models to evaluate water rights applications in the Middle Rio Grande (Albuquerque), Santa Fe, Estancia, and Lower Rio Grande (Las Cruces) basins. The evolution of the groundwater model for the Middle Rio Grande Basin, the most studied basin in the state, highlights the uncertainty in calculating river depletion that remains after nearly two decades of model development, despite the volumes of data and sophisticated computer simulations.

Development of the groundwater model began in the mid-1980s with the development of a steady-state flow model (Kernodle and Scott 1986). The steady-state model was subsequently revised to simulate transient flow and incorporated the assumption that groundwater pumping is fully compensated by river depletion, with no time lag between pumping and depletion (Kernodle et al. 1987).

A new transient model was later developed to include a more realistic representation of the hydraulic connection between the Rio Grande and the aquifer (Kernodle et al. 1995). This new model predicted that by the year 2020 only 44–63% of pumped groundwater will have come from the Rio Grande. By comparison, the Glover-Balmer model predicted that approximately 82% of the groundwater sought by a major industrial facility would be derived from depletion of the Rio Grande over a 25-year period (OSE 1994). The model was once again updated to include new information on the hydrologic framework of the basin, resulting in an approximate 7% increase in the estimated river depletion caused by groundwater pumping (Kernodle 1998). Kernodle's model was revised again to include new geologic and hydrologic data, such as observed baseflow gain/loss data for the Rio Grande surface water system, which had not been included in earlier modeling efforts. Still, the authors concluded that the model is not yet completely satisfactory and strongly suggested that further modifications need to be made (Tiedeman et al. 1998).

The State Engineer concluded that the stream depletions estimated by the Teideman model were quite high, closer to those calculated by the Glover-Balmer method than those calculated using the original Kernodle model or the revised Kernodle model (OSE 2001). The State Engineer revised the Teideman model to incorporate new hydrogeologic data and now uses it to estimate stream depletions for water rights applications. Comparison results show that the OSE model predicts stream depletion as approximately 10% less than that predicted by the Teideman model (OSE 2001).

The uncertainty associated with the stream depletions estimated by the numerical simulations suggests that senior surface water rights could be impaired if the actual impact of proposed groundwater pumping is underestimated (Minier 1999). The State Engineer recognizes the risk associated with the uncertainty in the numerical simulation approach to estimating future stream depletions. Impairment of surface water rights will not be easily remedied because depletion of the Rio Grande caused by groundwater pumping will continue long after pumping ceases. Uncertainty analysis could be applied to groundwater problems to evaluate the likely range of risk associated with groundwater pumping (Knowlton and Minier 2001). However, rather than perform an uncertainty analysis, the State Engineer has developed administrative guidelines for evaluating groundwater permit applications to prevent depletion of the fully appropriated Rio Grande.

The State Engineer does not rely on the evolving computer models to determine the amount of offset surface water rights a permittee must obtain in order to appropriate groundwater. Instead, the State Engineer limits new groundwater diversions to the amount of valid surface water rights held by the permittee, plus the amount of water the permittee returns directly to the river

(OSE 2000). The surface water rights held by the groundwater permittee are not immediately needed to offset groundwater pumping impacts because stream depletion may not occur until many years after pumping begins. But because of the uncertain availability of surface water rights in the future, the State Engineer requires that the permittee have those rights in hand before groundwater pumping begins. The State Engineer uses the computer model to evaluate the timing and magnitude of stream depletion for the limited purpose of determining the quantities of surface water the groundwater appropriator may lease for other purposes until the groundwater pumping begins to impact the river.[1]

The State Engineer addresses the uncertainty in the computer model by applying additional conditions to permit approvals in order to protect senior surface water rights holders. One condition is a general recitation of a water statute that says the permit shall not be exercised to the detriment of valid existing water rights. Another condition requires that the permittee monitor the water level decline and submit the data to the State Engineer. A third condition states that if the State Engineer finds that the rate of water level decline resulting from the proposed diversion is inconsistent with the State Engineer's projected water level decline and that existing water rights may be impaired, the State Engineer may order the permittee to reduce, or to stop entirely, groundwater pumping from the subject well.

The State Engineer has also developed administrative guidelines for the Estancia Basin which, unlike the Middle Rio Grande Basin, is a mined basin because it is not hydraulically connected to a perennial surface water source of recharge (OSE 2002). Accordingly, stream depletion by groundwater pumping is not an issue. The primary objective of the mined basin guidelines is to protect existing water rights in a basin with a finite stock of water. Under the mined basin guidelines, the State Engineer will consider applications to appropriate groundwater that are pending at the time the guidelines were adopted; new applications to appropriate groundwater will be summarily denied. The guidelines also allow the State Engineer to consider applications to change the locations of wells and the place and purpose of use.

Other states in the western United States have developed varying approaches to conjunctively managing surface and groundwater resources. Those approaches vary from being overly protective of surface water rights holders to providing almost no protection at all (Glennon and Maddock 1997).

The state of Washington, in the northwestern part of the United States, has implemented a conjunctive management system that has as its goals, the promotion of the health of the state through protection of existing rights related to the environment, such as minimum instream flow requirements, and promotion of the economic well-being of the state by encouraging maximum utilization of the state's water resources. One of the groundwater regulations conditions groundwater permits on the maintenance of minimum instream flows if there is "significant hydraulic continuity" between the surface water and the proposed source of groundwater. Because the regulations do not define it, interpretation of the phrase "significant hydraulic continuity" was defined by the state court that essentially found that *any* hydraulic continuity is significant, regardless of the magnitude of the effect of groundwater withdrawal on the stream (Minier 1998). In this case, the state issued the permit on the condition that the farmers would have to cease irrigating their orchards when flow in the nearby river, about a mile away, fell below its minimum instream flow levels. The court upheld the state's permit condition even though the proposed groundwater pumping would decrease the average mean flow in the river, approximately 1,391,280 gallons per minute, by only about 10 gallons per minute. Even at the river's low flow of over a quarter million gallons per minute, the decrease would amount to only 0.0037% of the low flow rate and would not be measurable in the river. The court's decision rendered the permit useless.

Arizona has a bifurcated system of allocating water rights (Supreme Court of Arizona 2000). Surface water is subject to the doctrine of prior appropriation. Surface streams not only flow above the ground but also have "subflow," which is considered part of the stream and is not considered percolating groundwater. Percolating groundwater may be pumped by the overlying landowner subject to the doctrine of reasonable use and is excluded from the legal rules applying to prior appropriation. The purpose of a general stream adjudication in Arizona is to determine the nature, extent and relative priority of the water rights of all persons in the river system and source, which in turn includes the identification of the "subflow zone". In the Gila River Adjudication, the Supreme Court of Arizona defined "subflow zone" as being immediately below and adjacent to a stream and excluded the adjacent tributary or basin-fill aquifers even though those aquifers may be hydraulically connected to the stream. No wells located outside the lateral limits of the subflow zone will be included in the adjudication unless the cone of depression caused by its pumping has *now* extended to a point where it reaches the subflow zone, and by continual pumping will cause a loss of the subflow as to affect the quantity of the stream. Such a definition ignores the scientific reality that pumping in every well in an adjacent aquifer that is hydraulically connected to the subflow zone will deplete the stream to some extent. Arizona's bifurcated system coupled with the court's definition of subflow does little to protect prior surface water rights from impairment by later reasonable use of percolating groundwater by landowners.

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[1] The State Engineer also uses the model to estimate whether the proposed groundwater withdrawal will result in excessive water level decline rates.

Reuse and the Conservation and Offset Potential of Reinjection and Reinfiltration

The statement is often made regarding surface water that all of the good reservoir sites have been developed and that there is no further opportunity for storage because there are no remaining canyon walls to which dams can be attached. As with most generalities, this particular one turns out to be untrue. In fact, there are numerous potential reservoir sites and those sites contain the double benefit of being less amenable to surface water pollution from runoff and providing almost no evaporative loss. Those "reservoir" sites are, of course, underground. Such natural subsurface reservoir sites have been known for years and utilized for groundwater stocks by societies for centuries. Every spring when floods spread across the alluvial plains, these reservoirs are recharged. Some have served to provide a permanent water source for phreatophytes, others have provided filtration to improve water quality and leach out salts.

Since the earliest days of settlements along stream systems, farmers have known that their survival in dry years could be ensured by utilizing the water in storage in the shallow alluvial aquifers that are adjacent to stream systems. This was done through shallow wells that might pump in a dry summer and the next year be recharged through high snowmelt runoff. This practice has become more sophisticated as it has evolved throughout the western United States.

The first manifestation of this phenomenon is reflected in programs to divert surface water in abundance during high runoff periods or when not otherwise needed, during a runoff year, into the ground through infiltration basins or through direct injection. A second involves the extraction and treatment of water of lesser quality that naturally exists in storage but previously has been left untouched because of the cost of treatment. A third involves treatment of effluent and industrial water that previously had been returned to streams to be diluted by cleaner water. This latter category holds tremendous potential because once treated to potable standards, this water can be placed in the aquifer to augment supplies, to offset the effects of groundwater withdrawals by mounding of the water table to protect streams from the effects of pumping from other wells, to improve the quality of existing water in the aquifer, and to augment surface flows through infiltrated groundwater.

Critical to these methodologies are fundamental policy decisions as to the standards for treatment prior to injection, monitoring and testing to ensure those standards are maintained, and methodologies for water accounting once the water is placed in the aquifer. States vary greatly in their approach to these issues.

Examples of Reuse and Water Quality Protection

The city of Dayton, Ohio, in the eastern United States, created an artificial recharge system beginning in the 1930s to keep groundwater levels high enough to allow for large drawdowns by high-capacity wells that provide groundwater for municipal and industrial use (Alley et al. 1999). The system diverts surface water from nearby rivers to a series of infiltration basins to recharge the underlying aquifer, and requires periodic maintenance to remove accumulated sediment from the basins.

In 1996, the state of Arizona created a water banking authority to maximize the benefit of the state's 2.8 million acre-feet share of Colorado River water. Rather than leaving its unused share of the water in the river to be lost forever to consumers in southern California, the water is delivered to central and southern Arizona via the Central Arizona Project where it then recharges the aquifer via infiltration basins and also by direct injection. The recharged water can then be pumped out and used in the future.

There is a research project in the Tularosa Basin, New Mexico, designed to evaluate technologies for desalination of brackish groundwater (Sandia National Laboratories and United States Bureau of Reclamation 2002). The Tularosa Basin is located in southeastern New Mexico and is home to the White Sands National Monument. Like many basins in the western United States, the Tularosa Basin contains substantial amounts of brackish groundwater that is generally not suitable for most uses. Development of economically feasible technologies to remove and dispose of the dissolved minerals in groundwater will open up important, new potential sources of water, especially in mined basins.

In 1986, the city of El Paso, Texas, built a 10-million-gallon-per-day plant that treats wastewater effluent to drinking water standards. The treated water is injected directly into the aquifer via wells. The recharged water spends approximately 2–4 years in the aquifer before it is withdrawn by production wells 0.25–4.5 miles away from the injection wells and is then put back into the City's water supply and distribution system.

There are at least 25 water reuse facilities in use or under construction, primarily in Arizona and California but also in some states in the eastern United States such as New York, that treat 0.5–19 million gallons of wastewater per day for various uses (Freeman et al. 2002). Those uses include aquifer recharge, irrigation, commercial and industrial uses, watershed augmentation, and seawater intrusion control.

Regulations for water reuse and aquifer recharge vary between states and depend on the type of reuse as well as the character of the aquifer to which the treated water will be discharged (USEPA 1992). Generally, any reuse involving human contact or discharge to aquifers that could be sources of drinking water require that the water be treated to drinking water standards. Other uses such as irrigation where human contact can be limited do not require as extensive treatment.

Long-term Policy Implications

The above discussion of the evolution of conjunctive and coordinated management of groundwater as well as surface water may provide a model for the marriage of science and law through judicial decision making. The state of New Mexico is hardly the wealthiest, but the "capacity building" that took place through the office of the State Engineer made its way into the judicial decision-making process. The inescapable logic of the scientific and practical approach to conjunctive management eventually was enshrined into the case law.

In contrast, there is the state of Arizona, which lacked a strong history of administrative regulation, and which has taken somewhat more of a "wild west" approach to private ownership of resources. The result has not been judicial decisions that are grounded in scientific fact, but an attempt to establish clear legal principles, even if they are not grounded in fact. Courts can only decide the cases before them and, if there is no inherent logic in the evidence presented, they will ultimately adopt their own rule based upon presumptions, whether or not those presumptions are ultimately based in fact.

The state of Washington presents a third case where the extensive capacity to make measurements of hydraulic and hydrologic parameters may have outstripped the rationale for why one makes measurements in the first place. Simply because one can measure a hydraulic connection between ground and surface water does not mean that the measurement provides any policy implications that require regulation.

Thus, the need for "capacity building" in institutions that choose to regulate ground and surface water together goes beyond lawyers to draft laws, hydrologists to measure impacts, or judges to make decisions. It encompasses the need for trained professionals that view all of the above skills as tools for crafting and implementing a set of rules that provide usable results that will sustain societies over time. The above examples hopefully provide a snapshot of the complexity of the societal processes that occur as these rules develop.

Conclusion

There can be no doubt that our technical knowledge of how to measure the yield of aquifers is growing exponentially. This is a result of the improving sophistication of computers that will process more and more equations and more sophisticated methods for utilizing those tools to model aquifers with an every growing number of parameters. Model results are useful because they help define the variations of the limits of aquifer productivity, predict land subsidence, measure directions and velocity of plumes of pollution, and they provide a better understanding of rates of drawdown in mined aquifers and the properties of the hydraulic connection between surface waters and adjacent aquifers.

Hydraulic modeling data does not, however, answer the questions society is asking itself regarding water resources. The question of what is the rate of drawdown does not answer the question of what the mining rate should be or whether or not mining of an aquifer in certain circumstances is appropriate. How readily a well draws water from a stream while simultaneously taking groundwater does not answer the questions of what is the best method, from a policy perspective, for allowing such impacts to occur and how best to protect other water users. A model result may tell us how much drawdown will occur over time in adjacent wells if a new well is pumped, but it does not answer the important question as to how much effect one can cause to another's well before that effect is too much and a permit for a new well should be denied. Finally, water quality data can tell us how clean water is before it is reinjected into an aquifer, but it cannot tell us how clean it should have to be before it is injected and how much risk can be tolerated in the process of monitoring treatment.

Too often, persons with technologic answers believe they are answering the important questions. Most often they are not. They are simply providing the data to answer the question—only a knowledgeable, thoughtful democratic society can ultimately respond to issues of policy. It is hoped that, as groundwater resources become more and more a source of vital supply, society provides us with wise answers.

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