Factors determining the economic value of groundwater[1]

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Abstract

Increasing groundwater extraction threatens aquifer sustainability for future generations. Making the best use of limited groundwater resources requires knowledge of its alternative extractive and non-extractive values, as well as the cost of extraction and the hydrological interlinkages between alternative uses. Groundwater value is driven by a number of factors including its supply and demand and institutional and policy factors. In this paper we describe these factors and how they affect value of groundwater. We describe the various components relevant to the economic valuation of groundwater and discuss potential difficulties in their practical estimation. We argue that groundwater management is essential when there are large potential spatial and temporal externalities related to groundwater pumping. Maintaining non-extractive and option values is likely to require trade-offs with current extractive uses. Well-informed management will be required to allocate groundwater efficiently between different users such as agriculture, industry and the environment, while also balancing the needs of current and future generations.

Keywords: Economic value, groundwater management, externalities, non-extractive values

Introduction

Groundwater extraction supports a range of agricultural, industrial and household water uses around the world. Conversely, non-extracted groundwater stocks can provide services, such as acting as a barrier against seawater intrusion or supporting natural flows critical to the functioning of ecological communities, and can have an option value for future uses, such as buffering periodic shortages in surface supplies. While groundwater is a renewable resource when recharge is present, aquifers have limited capacity, and recharge rates are frequently

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less than extraction rates. As populations grow and rainfall patterns change, groundwater resources are likely to come under increasing pressure.

Making the best use of limited groundwater resources requires knowledge of its alternative extractive and non-extractive values, as well as the cost of extraction and the hydrological interlinkages between alternative uses; therefore, collaboration between economists and hydrologists is essential to achieve this goal. This paper seeks to engage hydrologists with answers to questions that economists ask when trying to determine the best use of limited groundwater resources. What factors influence the economic value of groundwater? Should groundwater be used now or later? How do different water institutions lead to different water allocations across time and space? Why are understanding demand and supply equally important? To ensure the optimal use of scarce groundwater, resource managers must ultimately integrate sufficiently detailed hydrological and economic models that address these questions.

The paper proceeds as follows. Section two describes the standard economic framework for the optimal allocation of groundwater. Section three considers the 'supply side', that is the nature of the groundwater resource. Groundwater value is influenced by the capacity of an aquifer, its location, water quality (e.g. salt concentration), natural rates of recharge and discharge, potential extraction and artificial recharge rates, and links to other groundwater and surface water systems. Section four considers the demand side, based on the concept of total economic value. Concluding remarks are provided in the final section.

Economic framework of optimal groundwater management

From the standard economic perspective, optimal groundwater management is defined by the rate of extraction over space and time that maximizes the present value of benefits minus costs, subject to the physical hydrology of the aquifer and related water sources (Brown and Deacon 1972; Gisser and Sanchez 1980; Provencher and Burt 1993; Brozović et al. 2010). A descriptive solution to this dynamic optimization problem states that the marginal benefit or value of extracting an additional unit of water at all times and locations must equal the full marginal opportunity cost of extracting that unit of water.

Economists represent the marginal value of water in extractive uses with a demand curve. Downward sloping demand curves indicate that users allocate water to the highest value uses

first and subsequently to lower value uses, or equivalently that the marginal value decreases as more water is used.

The full marginal opportunity cost consists of the actual marginal cost of extracting a unit of water plus the present value of the increase in future marginal costs caused by the absence of that unit of water. The increase in future marginal costs falls into two general categories: the future increase in marginal costs of all extractors and the marginal reduction of future non-extractive benefits that depend on water stock or flows from that water stock.

Future marginal costs increase for all extractors because pumping an additional unit of groundwater reduces the total aquifer stock which creates two consequences for both the extractor and all other users. First, lower stock increases the depth to groundwater and consequently the pumping costs of all impacted users. This higher cost of pumping can persist indefinitely dependent on hydrological specifics. Those costs that extractors impose on other extractors are external to the market and mediated by the physical environment, economists call these negative externalities. Economists define the marginal pumping cost externality as the present value of the change in future pumping costs imposed on all other extractors as a consequence of pumping a unit of water today. Second, lower stock reduces future availability and decreases extraction alternatives for all users. If the stock constraint ever becomes binding (due to its quantity or quality) on future pumping decisions, economists define a marginal stock externality as the present value of the loss in net value arising from the non-availability of groundwater stock caused by pumping a unit of water today. One consequence of the stock externality is that part of the full marginal opportunity cost of extracting water depends on its value in use. For example, if seawater intrusion eliminates the water supply for a particular piece of irrigated farm land, then the future net productive value from that land is lost or minimised when alternative but more expensive water supply is available.

Other types of externalities are also possible. With a small number of extractors a strategic externality related to the pumping cost externality arises if extractors take into account the behavior of other extractors (Negri 1989). An extractor pumps more, realizing that pumping less will result in higher groundwater levels reducing the marginal cost of extraction for other extractors inducing them to pump more. Also, third-party impacts on groundwater quality may arise from extraction as well as other practices. Furthermore, groundwater extraction

can reduce surface water flows through hydrologic linkages, potentially causing damage to ecosystems and decreasing the quantity or quality of water available for other uses.

In a stochastic setting, additional values and costs arise. The existence of groundwater stock to use in conjunction with stochastic surface water supplies creates a buffer value, defined as "… the difference between the maximal value of a stock of groundwater under uncertainty and its maximal value under certainty where the supply of surface water is stabilized at the mean." (Tsur and Graham-Tomasi 1991). And for risk averse extractors, a risk externality arises because lower stock increases the income variability tied to stochastic surface water supplies as lower groundwater stocks are less able to buffer against stochastic surface supplies (Provencher and Burt 1993).

The allocations of groundwater which do not account for externalities may substantially deviate from optimal extraction desirable for maximising social welfare from the groundwater use and stock, both from current and future generations' perspective. If groundwater management policies are required to achieve sustainable extraction, a critical question is the design, implementation and enforcement of such policies. Formulation of appropriate groundwater management policies or institutions is essential for economically efficient, environmentally sustainable and socially acceptable allocations. Economic rationality in design, political sensitivity in implementation, and close and constant attention to political–economic interactions and social-institutional factors is critical for the success of these institutions, as they determine in each case the dynamics to follow (Koundouri, 2004).

Groundwater supply: The nature of the resource

Understanding the hydrology and ecology of the groundwater source and groundwater surface water interactions is critical for evaluating the interlinkages between alternative extractive and non-extractive uses. Hydrologic information includes factors such as: rainfall, runoff, and infiltration; depth, whether the water-bearing zone is confined or unconfined; groundwater flow rates and direction; type of vadose (shallow water zone) and water-bearing zone materials, and groundwater influence on stream base flow, lakes and wetlands.

Figure 1 summarises the linkages between these key hydrologic factors and direct human influences via extraction and artificial recharge. Aquifers can be thought of as natural assets composed of an existing stock and quality of water, a storage capacity and a distribution

capacity. In their natural state, aquifers are a balance between discharge (e.g. into surface flows) and recharge (from rainfall). There may be substantial time lags between rainfall and groundwater aquifer recharge capacity; additionally recharge rates are highly variable. Some aquifers (such as the Burdekin Delta aquifer in northern Australia, the Romeral aquifer in north-central Chile and the Carrizo-Wilcox aquifer in Texas) are naturally rapidly recharging, while others (such as the Great Artesian Basin aquifer in Australia, the Ogallala or High Plains aquifer underlying the Great Plains in the United States and the Gulf Coast aquifer in Texas) are slow recharging aquifers (Scanlon et al. 2003). The contribution of rainfall to recharge depends among other things on soil type and vegetation. A recent Australian study found higher recharge rates under annual vegetation than perennial vegetation and under coarse textured soils than heavy clays (Crosbie et al. 2009). Disturbances to natural recharge can affect groundwater quantity and quality. For example, land clearing or land use change can result in dramatic modifications in the water balance affecting recharge capacity and groundwater quantity and quality (Favreau et al. 2009).

Figure 1 near here

Climate change is expected to reduce rainfall in many regions across the world (IPCC 2007; Shindell et al. 2006; CSIRO 2008), which is likely to result in both reduced groundwater recharge and increased demand for groundwater extraction (Shrestha and Kataoka 2008; Zagonari 2010). One management option is artificial recharge, deliberately conveying water to the saturated zone, which can be used to top up a declining aquifer. This occurs in some large aquifer systems such as the Burdekin Delta in north Queensland, Australia (Bristow et al. 2003; Qureshi et al. 2007) and the Tucson Basin in Colorado, USA (Al-Sabbry et al. 2002). Recharge can also occur through excessive irrigation where a portion of the water applied is not consumed by crops and either enters into deep drainage, reappears downstream or recharges the local aquifer (Qureshi et al. 2010a; Shukla and Jabel 2006). For example, a study in the Campaspe River Basin in Australia found that 15% of applied irrigation water recharged the shallow aquifer (Chiew and Mahon 1991).

The quality of groundwater has a significant effect on where and how it is potentially used. Aquifers containing only slightly mineralised water are suitable for the widest range of uses, including for drinking water, while poorer quality sources may be restricted to certain agricultural or industrial applications. In agriculture, for example, poor quality groundwater

reduces crop yield; however within limits farmers may be able to blend it with fresher surface water to expand irrigation opportunities. Treatment can make poor quality groundwater useful for a broader range of purposes, but this comes at a cost.

In some instances groundwater extraction can reduce the future storage capacity of the aquifer or affect its quality. For example, leakage of contaminants into aquifers (from agriculture, mining and other sources) may reduce the future range of uses and values available (FAO 1996; FAO 2003; Msangi and Howitt 2006). When seawater intrusion eliminates the good quality water supply for a particular irrigated area, then the future net productive value from that land is lost or reduced (when a more tolerant crop is grown). If substitute transfer water could be delivered through infrastructure built to replace the natural conveyance and distribution capacity of the intruded aquifer, then the increase in the marginal cost of water (infrastructure, operations, and water source costs), and consequently lower output and revenue, may be thought of as the cost of the loss of groundwater availability. Groundwater extraction has resulted in seawater intrusion into aquifers in the Burdekin Delta (Bristow et al. 2003; Narayan et al. 2003) and in the Salinas Valley of Monterey County, California, which is the top-ranked vegetable-producing county in the USA (Reinelt 2005; USDA 1999). Qureshi et al. (2007) estimated the cost of using surface water which substituted groundwater use which became brackish in areas where sea water intrusion took place. In intruded areas of the Salinas Valley, farmer per unit average water cost increased 267% to approximately $215/ML, with the cost to replace the conveyance and distribution functions being slightly more than the cost of replacement water stock from a combined reclaimed urban wastewater treatment and enhanced surface water system (Reinelt 2005; MCWRA 2007). A prior economic study of the region (Green and Sunding 2000) indicates this cost increase would halt planting of some low value summer crops, but mainly would directly reduce profits from high value strawberry crops and spring and fall vegetable crops. Similarly, extraction can lead to land subsidence and reduced future storage capacity (Bell et al. 2002), which can reduce or eliminate the value of the aquifer to all other current and future users.

Groundwater extraction can reduce surface water flows causing damage to ecosystems and decreasing the quantity or quality of water available for other uses. In the western United States, conflict over surface water impacts of groundwater pumping has occurred related to both the protection of endangered species (e.g. in California, Idaho, and Texas; McCarl 1999;

Smith 2008; Associated Press 2010) and to interstate compacts governing the allocation of transboundary rivers (e.g. in Nebraska, Kansas, Colorado, New Mexico, and Texas; McKusick 2002; Hathaway 2010). In Australia's Murray-Darling Basin, reduced surface water allocations due to recent droughts has increased groundwater pumping by an estimated 447 GL/year and reduced annual stream flow by 840 GL/year (CSIRO 2008).[2] Groundwater extraction can also impact wetland and lake ecosystems (National Academy of Sciences 1997).

Groundwater demand: Components of total economic value

Groundwater valuation is an important step for achieving sustainable groundwater extraction. Valuation of groundwater resources in alternate uses can provide important information to decision makers in establishing equitable and efficient groundwater management policies. Societies derive many benefits from groundwater services that can be classified into two broad categories: extractive values (or use values) and non-extractive values (in-situ or non-use values). Together they comprise the total economic value as illustrated in Figure 2. Extractive values are further subdivided into direct use values (such as municipal/urban, agriculture, industrial or mining) and indirect use values (such as biological support of groundwater dependent ecosystems and supporting recreation value at discharge sites). Non-extractive values include buffering value (which is also an option value), subsidence avoidance, water quality protection and prevention of sea water intrusion. In addition to values for current uses, there are also option values for future uses (which may be extractive or non-extractive), including both the value of groundwater to current users in the future and the bequest value of groundwater to future generations.

Figure 2 near here

Extractive use values are the most amenable to being expressed in monetary terms, and in some instances market trades can provide useful data for estimating these values. Extractive use values vary between users, and also vary for individual users depending on how much water is available to them. Market prices provide a reasonable proxy for values, since they provide a real measure of users' willingness to pay for water. However, it should be noted that market prices only reflect the value of water at the margin (i.e. where demand meets

[2] One GL (gigalitre) is one million litres and is equal to 811 acre feet.

supply). At the margin extraction cost can be effective in describing households' willingness to pay. For an industrial or agricultural firm, the marginal value of water equals the net increase in the value of output (product) from using an additional unit of water.

The extractive value of groundwater is dependent on its proximity to both potential users and alternative sources of water supply. Agriculture is typically the largest user of water, but the marginal value of water in agriculture is often lower than in other sectors such as household, mining and manufacturing. The extractive value of groundwater depends both on what it is used for, and when. There is often greater flexibility in the timing of groundwater use relative to other water sources since it is less subject to seasonal fluctuations. However, if the rate of extraction exceeds the long-term recharge rate of an aquifer, its use also entails an opportunity cost, through foregoing opportunities to use the resource in the future. If less groundwater is available in the future, there will be less opportunity to buffer stochastic surface water supplies, resulting in increased risk for water users (Provencher and Burt 1993). The value of flexibility in when and how the resource is used is described by option values.

As an example, consider the value of groundwater for agricultural use. When groundwater is used for irrigation it may supplement a supply of surface water, such as rainfall. Since the surface water supply is typically stochastic (as it is dependent on short-term rainfall), the stock of groundwater serves two purposes: a) an increase or substitution in the overall supply of water; and b) as a buffer against fluctuations in the availability of surface water (Tsur and Graham-Tomasi 1991). Buffer values will be particularly high in perennial crops such as orchards or vineyards, where groundwater can enable to plants to survive through periods of low rainfall, protecting the value of the investment. Qureshi et al. (2010b) estimate that the value of water can be an order of magnitude higher when it used for perennial crops than for annual crops which have little or no capital cost. This value depends on the age of the crop; younger orchards and vineyards represent an investment with a longer potential lifespan and hence greater future income potential compared to older plantations (Qureshi et al. 2010a).

There are also a range of risk and uncertainty considerations in assessing groundwater values. These arise from the influences of economic uncertainties and events that take place at local, regional, national, or international levels. For example, changes in commodity prices, local policies and international markets can affect the value of the groundwater used to produce

those commodities. They also extend to key hydrological and economic variables, such as the impacts of climate change, energy costs and hydrology on pumping costs, and changes in the quality of groundwater. New extraction technologies or new applications for groundwater may also affect its value in the future.

Critically the impact of uncertainty on groundwater values is linked to uncertainty around alternative water supplies, which is high under climate change. In this environment consideration of real options analysis techniques, which allow estimation of the option value of retaining flexibility over future groundwater use under conditions of risk, will be necessary to estimate values with any accuracy (see for example Mezey and Conrad 2010). However, option values can never be captured completely since they are dependent on both known unknowns such as future commodity price fluctuations and unknown unknowns such as future technology changes. As climate change impacts on surface water availability, the future value of groundwater may be significantly higher across a range of uses including agriculture.

Groundwater can support agriculture in areas that would otherwise prove too arid and can increase agricultural productivity in semi-arid areas. Increased agricultural profits related to irrigation can be capitalized into land rents and the market sale prices of agricultural land. Hedonic studies of the capitalization of *surface* water rights have found that irrigation increases sale prices of land (e.g. Xu et al. 1993; Faux and Perry 1999). Conversely, hedonic studies of the capitalization of groundwater availability into farmland values have found mixed results. Hartman and Taylor (1989) found that groundwater did not have a significant effect on sale prices of agricultural land in Colorado in the United States. A large study by Torell et al. (1990) that included Colorado, Kansas, Nebraska, New Mexico, and Oklahoma (all of which overlie the Ogallala aquifer in the United States) found a positive effect of groundwater irrigation on sale price, though with declining price differentials between irrigated and non-irrigated land over time. Torell et al. (1990) suggested differences between studies were driven by regional differences in aquifer saturated thickness and measures of farm income. Another possible explanation for observed insignificant capitalized values of groundwater irrigation is that groundwater is generally private property and its use is not regulated. Without regulations in place the option to implement irrigation in the future exists and so the *potential* value of irrigation may be capitalized into the price of both currently irrigated land and dryland.

Enforceable restrictions on groundwater use should thus affect its value as capitalized into land markets. Petrie and Taylor (2007) examined the impact of a change in institutions, in the form of a moratorium on groundwater use permits, in Dooly County (Georgia) in the United States. They found that before the moratorium was announced, there was no difference in the market prices of agricultural land with or without permits to pump groundwater. However, after the moratorium, land with attached groundwater permits sold for about 30% more than land without permits. In effect, introduction of the moratorium removed the option to use groundwater on land without permits, thus reducing possible future profits.

Institutions[3] that regulate groundwater use can impact its economic value in multiple ways. For example, rules requiring annual use will tend to drive direct substitution with surface water, while accounting across longer time periods may encourage more complementary uses with other sources, which can have a higher value. Regulation becomes particularly important when there is trade off between short term usage of a resource and its longer term resilience, for example if excessive extraction could result in an irreversible loss of an aquifer. According to Katic and Grafton (2011) when the threshold at which an irreversible impact occurs is uncertain, controlling both the rate and depth of extraction can generate a higher economic return (value) and a lower probability of crossing the threshold than only controlling the rate of extraction.

One type of institution for allocating groundwater that is receiving increasing attention is private water markets (NWC 2011; Parris 2010). Well organised functioning groundwater markets offer the potential to allocate groundwater efficiently and generate enhanced economic outcomes. However, due to the difficulties and costs in designing properly functioning groundwater markets (i.e. property rights must be defined, allocated, monitored and enforced) and the transaction costs involved in creating and participating in such markets, the gains to society need to be sufficiently large to ensure a net benefit results (Coggan et al. 2005). However, in areas where groundwater pumping is metered and pumping restrictions have been put in place and enforced (such as in the Nebraskan portion of the Republican River Basin in the United States and McLaren Vale in South Australia), informal

[3] An institution is a structure or mechanism of social order and cooperation governing the behavior of individuals within a society.

groundwater markets are present even with large transaction costs, suggesting that the potential benefits from market-based groundwater reallocation are large (Palazzo 2009).

A particular issue that has received little attention in the literature is the interaction between institutional design in surface water markets and groundwater markets (Grafton et al. 2009) and the resulting value of groundwater to users. Policy factors, such as carry over rules (i.e. allowing farmers to carry forward some of their water allocation in one year to the next year), restrictions on surface water use or rules related to surface water storage capacity can affect the value of groundwater. Carry over rules in surface water markets (for example) can impact the value of complementary surface and groundwater access. Alternatively, groundwater use rules which encourage or restrict farmers to use a specific groundwater entitlement within an annual period will reduce the potential to switch from one source to another across longer periods of times. The effectiveness of such rules in groundwater management is dependent on the recharge capacity of the aquifer. For example, less groundwater use in one year in a rapidly recharging aquifer will result in less storage capacity available for recharge in the next and reduce net economic value added by the carry over rule. In a slow recharge system the opposite may occur, where annual extraction may stimulate groundwater mining. Critically, aligning private decisions with aquifer hydrological parameters will allow for better decisions to be made, and in some instances for option values to be internalised more fully in individual decisions.

An important issue in determining the total economic value of groundwater is the consideration of future generations. The practice of discounting future benefits can result in decisions which are profitable in the short term but impose substantial costs into the future. Standard economic models weigh the wellbeing of future generations less than that of the current generation, since at even relatively low discount rates (e.g. 5% per annum), costs which occur just a few decades ahead are discounted towards zero. The choice of discount rate is a contentious issue. For short-term decisions (i.e. groundwater allocation over a few years), discount rates based on the market cost of capital (i.e. the interest rate) may be appropriate, but for longer term decisions (i.e. decades or more) it may be more appropriate to use much lower discount rates (see Frederick 2006; Stern 2006; Gollier and Weitzman 2010).

Indirect use and non-extractive values, which may be biological, physical, social or cultural in nature, influence the wellbeing of individuals and cannot be easily quantified in monetary terms. This is because markets for these types of groundwater services either do not exist (especially for non-extractive values) or are highly imperfect, so much of the information needed for valuation is not readily available. Non-market valuation techniques can be used to estimate these values, though there are numerous methodological challenges and controversies (National Academy of Sciences 1997; Wilson and Carpenter, 1997).

Maximising the value realised from a groundwater resource requires trade-offs to be made between the benefits (or costs) in one period (such as the present) against the benefits in a different time period (i.e. future years); users of the resource must balance the desire for current consumption against a desire for consumption in the future. For groundwater managers, the challenge is to balance current and subsequent uses of groundwater stocks by maximizing the present value of the net benefits derived from the limited resource. The difficulty in estimating values in a common unit (e.g. dollars) complicates comparisons of alternative uses for groundwater, particularly of alternative extractive and non-extractive uses. Even when it is impossible to estimate non-extractive values accurately, measurement of extractive values of groundwater serves an important policy role. Alternative policies to restrict groundwater use will impose different magnitudes and distributions of costs (in the form of reduced profits) on groundwater users, and decision makers must understand how policies will affect relevant stakeholders in order to understand whether policies will be implementable. For example, policies with similar expected hydrological and ecological impacts might have a very different cost-effectiveness in terms of changes in groundwater users' profits.

Conclusions

Groundwater is a finite resource as aquifers have limited capacity and natural recharge is often lower than extraction rates. As a result, aquifers in many arid and semi arid regions of the world are being depleted. Understanding the hydrological characteristics and alternative extractive and non-extractive values of groundwater can help in making the best use of groundwater resources. The total economic value framework described in this paper can assist in identifying and estimating groundwater values. Understanding the supply and demand factors which determine the value of groundwater can help resource managers in better understanding groundwater stock and flow values. The ultimate aim must be to create a

balance between current and future uses of groundwater and to maximise the expected net present value of all benefits derived from a resource. Institutions for groundwater management should be designed to protect those values which are important but for which no market value is likely (i.e. where there are missing markets) and must reflect the physical parameters of the aquifer (storage capacity, recharge and discharge rates, potential extraction rates and artificial recharge opportunities). They should also reflect the inherent uncertainty around future values of groundwater, particularly under climate change.

Investment in effective management institutions is most warranted where groundwater resources have high extractive use values, while also having significant non-extractive and option values. The complexity of the required management is likely to vary with the degree to which use decisions align with aquifer parameters. For example, rapidly recharging, large storage space aquifers, where the actions of individuals do not affect other users, will tend to require weaker and less complex institutions than where this is not the case. Furthermore, where option values are high, institutions that ensure that the needs of future users are taken into account are more likely to be required.

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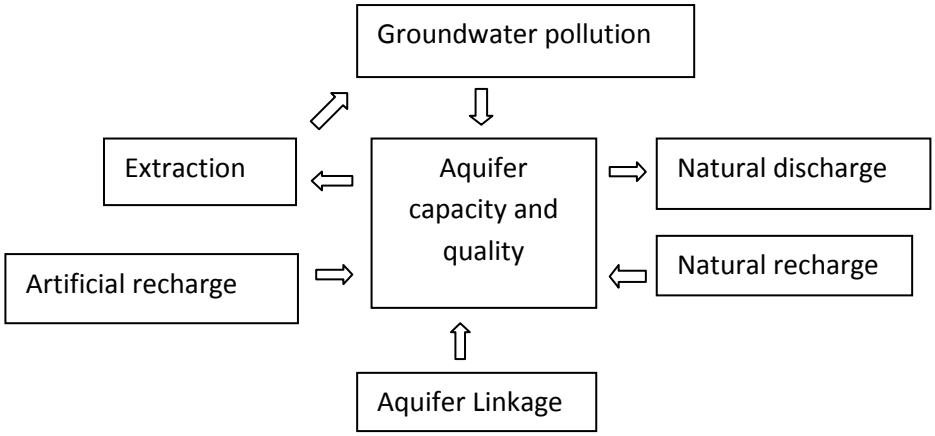

Fig. 1 Characteristics of groundwater quantity and quality relevant to economic valuation

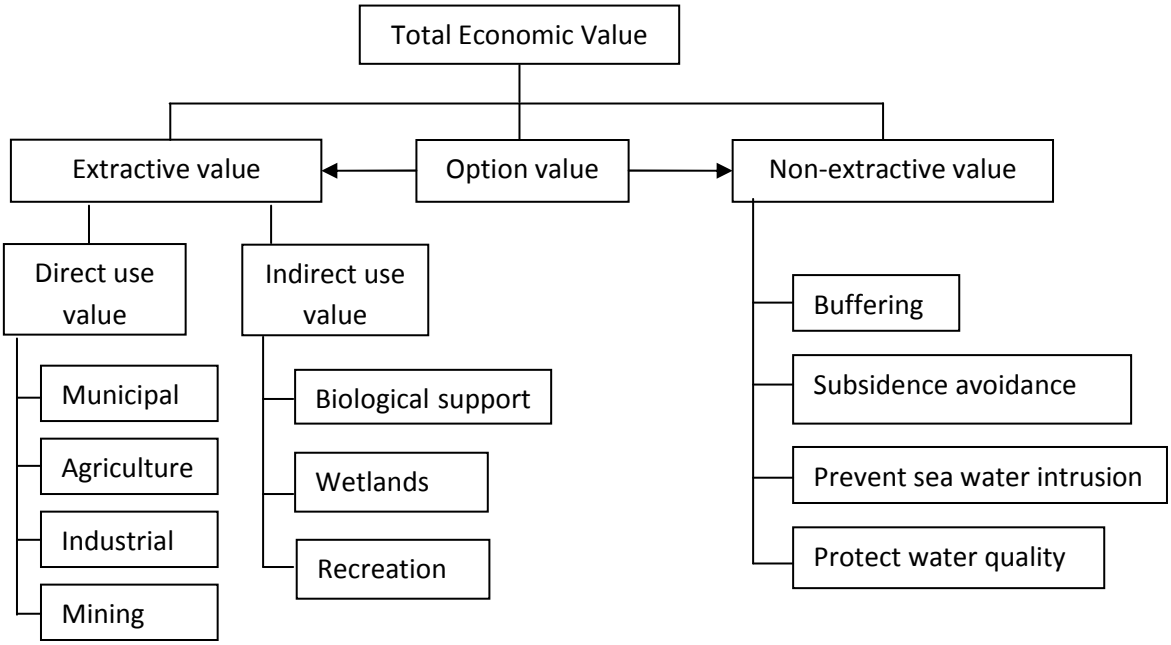

Fig. 2 Representation of total economic value and factors that determine groundwater value