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Article

Economics of Managed Aquifer Recharge

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Abstract: Managed aquifer recharge (MAR) technologies can provide a variety of water resources management benefits by increasing the volume of stored water and improving water quality through natural aquifer treatment processes. Implementation of MAR is often hampered by the absence of a clear economic case for the investment to construct and operate the systems. Economic feasibility can be evaluated using cost benefit analysis (CBA), with the challenge of monetizing benefits. The value of water stored or treated by MAR systems can be evaluated by direct and indirect measures of willingness to pay including market price, alternative cost, value marginal product, damage cost avoided, and contingent value methods. CBAs need to incorporate potential risks and uncertainties, such as failure to meet performance objectives. MAR projects involving high value uses, such as potable supply, tend to be economically feasible provided that local hydrogeologic conditions are favorable. They need to have low construction and operational costs for lesser value uses, such as some irrigation. Such systems should therefore be financed by project beneficiaries, but dichotomies may exist between beneficiaries and payers. Hence, MAR projects in developing countries may be economically viable, but external support is often required because of limited local financial resources.

Keywords: MAR; ASR; economics; cost-benefit analysis; aquifers; policy

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1. Introduction

Managed aquifer recharge (MAR) is defined as "intentional banking and treatment of waters in aquifers" [1]. The term MAR was introduced as an alternative to "artificial recharge", which has the connotation that the use of the water was in some way unnatural [1]. MAR includes a great diversity of technologies to store and treat water including aquifer storage and recovery (ASR), infiltration basins, salinity barriers, soil-aquifer treatment, and riverbank filtration. The water resources management benefits of MAR are compelling. However, the question arises as to why MAR has not yet been implemented to an even greater degree. The answer often lies in that decision makers, such as water utility managers, water management agency officials, and political leaders, have not been provided an equally compelling, sound economic case for investment in the technologies.

Investments in infrastructure, whether for water or other purposes, need to be justified in terms of the benefits of the project equaling or exceeding the construction and operational costs. The costs of the projects should also be less than the costs of alternative projects that provide the same benefits. Cost–benefit analysis (CBA) can be used to evaluate MAR projects, where their costs and benefits can be accurately quantified in monetary terms. However, economic analyses of water projects are often hampered by the difficulty of accurately quantifying the value of water, which can vary greatly depending upon circumstances. Todd [2] in a pioneering paper noted with respect to the economics of groundwater recharge that "It is clear the analysis of the benefits of artificial recharging is dependent on what value can be assigned to a unit volume of water" and "in assessing the benefits of artificial recharge, consideration must be given to the importance of water to the total economy, to the value of water for various uses, as well as to the direct and intangible benefits that may accrue."

Water and wastewater projects are not necessarily evaluated solely based on their profitability to the system owner and operator. Water and wastewater utilities often have mandates to provide specified levels of services irrespective of the profitability of each individual system component. Water has social and environmental values as a necessity of life. Hence, water is often provided to poor communities even if the revenues generated do not cover costs. Governmental projects are also often funded all or in part by general revenues (rather than entirely from revenues from the sale of water) with the goal of achieving societal benefits. MAR projects may thus be economically evaluated by comparison to non-managed scenarios [3] or other water management or treatment options to achieve the same goals [4,5]. The feasibility of MAR projects also depends upon financial feasibility [6], which addresses whether funding is available for a project and how a project will be paid for. In developing countries, MAR projects are available that may be economically feasible (*i.e.*, their benefits exceed costs) and could materially improve the quality of lives of the people, but financial resources are not available. Water projects often have to compete for limited financial resources against other types of projects (e.g., health, transportation) that also provide societal benefits.

The procedures for analyzing the economic benefits of groundwater presented by Bergstrom *et al.* [7] and the National Research Council [8] provide a basic framework for evaluating the economics of MAR systems. The first step in the evaluation is an analysis of the changes in groundwater quality and quantity resulting from the implementation of a MAR project. The change is evaluated relative to a reference state, which would normally be current conditions. The changes in groundwater services resulting from the change in groundwater quantity and quality is next evaluated. Finally, the economic value of the change in groundwater services is evaluated.

Water has been recognized to be an economic good, but its price is seldom set by a free market. Water also has social and environmental values that are difficult to quantify in monetary terms. Indeed, some people object to the very notion that economics should enter into decisions concerning water supply. The value of water also varies greatly depending on local circumstances. As water is critical for life, water can be priceless during extreme shortages. In some water-scarce developing countries, there are often large social costs associated with both physically obtaining the daily water supply and health impacts associated with poor water quality. On the contrary, during periods of abundant supply, the market value of water can be very low, and in the case of flooding it is a liability (*i.e.*, has a negative net value).

2. MAR System Types and Benefits

MAR includes a wide variety of processes by which water is intentionally added into an aquifer or induced to flow into and through an aquifer for treatment purposes. MAR, as defined by Dillon [1], includes two main end-member types of technologies: (1) methods that are used primarily to increase the volume of water stored in aquifers; and (2) methods that are used primarily for water or wastewater treatment. MAR systems with a water storage goal include ASR, aquifer recharge using wells and infiltration basins, and river channel modifications to enhanced aquifer recharge (e.g., check dams). MAR using wells, including specifically aquifer storage and recovery (ASR), was reviewed by Huisman and Olsthoorn [9], Pyne [10], and Maliva and Missimer [11]. Surface spreading methods were reviewed by Huisman and Olsthoorn [9], Oaksford [12] and Roscoe Moss Company [13]. The benefit of storage-type systems is the net increase in the volume of water stored in the aquifer. The increased storage results in an increase in the volume of water available for later beneficial use (abstraction benefits). Additional potential benefits result from the water being in place in the aquifer (*in-situ* benefits). *In-situ* benefits include reduced groundwater pumping costs, and avoidance of the need to replace or deepen production wells, restoration or maintenance of environmental (e.g., spring) flows, avoidance of land subsidence, and prevention of saline-water intrusion [2,8].

MAR systems with a storage goal are primarily constructed in hydrological and engineering settings where there are at least periodic shortages of water and times when excess water is available that could be used to recharge aquifers. MAR is used in arid and semiarid lands, for example, to capture surface water that is episodically available during uncommon rainfall events. MAR is also employed in areas with humid climates, such as South Florida and parts of India, where there is a pronounced seasonality in rainfall. The systems are usually installed either where excess water is available (e.g., in-channel and off-channel infiltration systems in ephemeral streams and ASR systems at water treatment facilities) or where the water is used.

MAR systems with a primary treatment goal have been termed "aquifer recharge and recovery" (ARR) and include soil-aquifer-treatment (SAT) and aquifer storage transfer and recovery (ASTR). SAT is a high-rate land application system that involves the spreading of partially-treated domestic wastewater on the soil surface to provide natural treatment as the water infiltrates into the soil and flows through underlying aquifers. The vadose (unsaturated) zone is used as a natural filter to remove or reduce the concentrations of suspended solids, biodegradable organic matter, nutrients, metals, and pathogenic microorganisms, by a variety of filtration, sorption and biologically mediated reactions [14–18]. Additional filtration and removal of contaminants occurs as the water travels through the aquifer. ASTR involves the injection of water into an aquifer using wells and its recovery with separate production wells as a means of improving stored water quality by providing additional residence time and to take advantage of the filtration and other treatment processes provided by the aquifer [19]. The essential, defining feature of ASTR is the intentional use of water flow through an aquifer as a treatment method.

MAR systems vary greatly in their scale and thus how they should be evaluated by CBA. Large-scale systems owned and operated by water utilities or water management districts or agencies usually have well-defined costs and benefits, although there may be uncertainty in the quantification of benefits (e.g., monetary value of stored water in the absence of a free market). MAR also includes small-scale systems implemented in developing countries whose benefits, such as a reduction in labor, disease, and mortality due to the availability of a more convenient, reliable, and safer water supply, are difficult to express in monetary terms, but nonetheless have great value.

3. Cost-Benefit Analysis

According to the basic rule of benefit maximization, in which increasing the total value of scarce resources is assumed to be desirable, actions (such as the construction of MAR systems) should be undertaken if their total benefits exceed total costs [20]. Cost–benefit analysis (CBA) is addressed in microeconomic textbooks and some dedicated books (e.g., [21,22]). Environmental CBA is a specific area of investigation (e.g., [23–26]), which includes issues of water quality and supply.

The underlying goal of CBA is allocative efficiency. Policies should be adopted or investments made only if they provide net positive benefits. The policy or investment that yields the greatest net benefits should be selected. A limitation of CBA is that goals other than economic efficiency (e.g., equity and national security) may be of relevance to the policy [22]. CBAs are not performed in a moral vacuum and the social desirability of a particular set of costs and benefits may be a consideration [25]. However, even if decisions are not made solely on the basis of CBA, decisions should at least be informed by CBA such that it is at least an input into the decision-making process [25].

CBAs are commonly performed using the net present value (NPV) method, which considers both the initial investment in the project and benefits and costs expected to be achieved or incurred over the life of the project. Future benefits and costs are discounted at an appropriate rate. The basic NPV equation is

$$NPV = -C_0 + \sum B_i/(1 + r)^i - \sum C_i/(1 + r)^i \quad (1)$$

where C_0 is the initial (capital) costs in year 0; B_i and C_i are the benefits and costs in year "I" and "r" is the discount rate.

Cost-effectiveness analysis (least cost analysis) and lifecycle costs analysis consider only the costs to achieve a pre-set objective or criterion. Different options are considered that provide the same benefit or set of benefits. Cost-effectiveness analysis is suitable where valid and reliable estimation of benefits is not feasible [27]. It may be used to evaluate options to achieve a well-defined water supply or environmental goal. For example, if the decision is made to supply a given amount of potable water to a community as a social objective, then cost-effectiveness analysis could be used to evaluate different supply options. A limitation of cost-effectiveness analysis is that an entire list of projects could be ranked without any assurance that any of them are actually worth doing [25].

A basic requirement of CBAs is that accurate costs and benefits values be used. However, "appraisal optimism" is common, which is the tendency to exaggerate benefits and under-estimate cost escalations [25]. Appraisal optimism can be either accidental or intentional. In the latter case, those with a vested interest in a project may under-estimate costs or over-estimate benefits to gain support for a project, knowing that projects develop momentum for their continuation and thus become difficult to later terminate. For example, false economic analyses were widely used to give the perception that major water supply projects in the western United States made economic sense, when in fact they could never be economically justified because the farmers (the primary beneficiaries) could never afford the true cost of the delivered water [28].

The discount rate reflects time preference for benefits and costs, which varies between individuals. Individuals typically value a benefit more today, than they would value receiving the same benefit ten years from now. Discounting enables comparison of costs and benefits that occur at different times.

In economics, the discount rate is equal to the interest rate in a perfect capital market with no taxes or inflation [29]. Application of a discount factor reduces the importance of future costs and inevitably means that what happens long distances into the future has very little impact on decisions made today [30]. Discounting has been referred to as a "tyranny" that militates against the interests of future generations [24] and thus appears to be inconsistent with rhetoric and spirit of "sustainable development" as it violates the notion of intergenerational equity [25]. However, not discounting (*i.e.*, use of discount rate of zero) creates other problems in that the needs of generations very far into future are given equal weighting, which would encourage excessive saving at the expense of current needs [25]. Pearce *et al.* [25] present the arguments that a time-decreasing discount rate may be the most appropriate solution.

There is considerable disagreement as to what discount rate is appropriate. Freeman [29] suggested that a rate of 1%–4% is usually appropriate. Where the costs precede benefits, as is the case for most water projects, those who favor such projects may argue for a low rate while those who oppose them may argue for a high rate [23].

Not all costs and benefits of a MAR project are borne and accrued by the system owner. For example, all groundwater users in a basin may benefit from increased water levels in an aquifer resulting from a recharge program, whether or not they personally financially contribute to the project. Similarly, where a project receives external funding, such as a governmental grant, the system owner and participants may receive most or all the benefits of a system, while not having to pay the full costs. The results of a CBA that include all costs and benefits may thus differ from the results of a CBA that is limited only to the costs and benefits to the system owner. This dichotomy is addressed under finance.

It is important to also distinguish between financial CBA, which measures only the direct financial implications of a project, and social cost-benefit analysis, which measures the overall welfare impact of a project [31]. Social benefits associated with water projects include benefits associated with having a reliable, convenient, and safe source of water. Welfare impacts can also be considered to include environmental benefits and costs. Valuation of welfare effects in monetary terms brings with it problems and can lead to inappropriate interpretation of results due to the lack of agreement on appropriate valuation methodologies and a lack of evidence to support the underlying values of some variables used in the analysis [31].

CBA has been used to evaluate MAR projects with an environmental restoration goal, such as the proposed 6.06 Mm^3/d (1.6 billon US gal/d) ASR system for the Comprehensive Everglades Restoration Plan (CERP) in Florida (USA) [32,33]. Although explicit legal requirements to return damaged ecosystems to baseline functioning may be desirable from an ecological perspective, from an economic perspective it is important to know whether restoration costs generate environmental benefits of equal or greater magnitude [34]. The challenge lies in providing a defensible monetary evaluation of ecosystem services and, for water projects, how those services are affected by variations in water supply. There is a school of thought that CBA, particularly as it is widely applied, is not appropriate because it fails to adequate consider environmental costs and values (*i.e.*, externalities). It has been proposed that ecosystems, such as wetlands, have an existence value, which can be derived simply from the satisfaction of knowing that some feature of the environment continues to exist [24,35]. Ecosystems are also considered to have an intrinsic value, irrespective of the utility or the desires of humans, which lies beyond the scope of CBA.

4. Costs of MAR Projects

The costs of MAR projects include both capital, operations and maintenance costs, and finance costs (debt service). Capital costs are fixed, one-time expenses incurred during the design and construction of the MAR system. Capital costs include, but are not limited to:

- Land;
- Testing costs, feasibility analyses;
- Consulting services for the design, permitting, and supervision of the construction;
- Construction costs (e.g., roads, piping, instrumentation, controls, and pretreatment systems); and
- Regulatory testing requirements during construction and operational testing.

Operation and maintenance costs include the following:

- Labor (system operation, regulatory requirements, administration);
- Electricity;
- Consulting services;
- Regulatory testing requirements (e.g., water quality testing);
- Maintenance costs (e.g., parts replacement, well and basin rehabilitation);
- Pre-treatment costs (additional treatment prior to recharge);
- Post-treatment costs (e.g., chlorination); and
- Raw water costs.

Costs used in the CBA should be marginal not average costs. Sunk costs, which are costs that would be incurred whether a project proceeds or not, should not be included in the CBA. Sunk costs include items such as previously performed hydrogeological investigations, existing wells that are no longer used, and existing intakes and piping. The marginal operational labor cost is zero if existing plant staff can operate the system (*i.e.*, there is no increase in total labor costs). Labor costs are included in the CBA if additional staff (or contracted labor) are needed to operate and manage the system.

CBAs should consider opportunity costs associated with land. Opportunity costs are the benefits one could have received by taking an alternative action. In the case of land, it could be revenues that could have been obtained if the property was sold or rented, or the value of goods and services that would have been obtained if the land were put to an alternative use. MAR systems that utilize wells have minimal surface footprints and, if carefully sited, do not preclude other land uses. Therefore, the opportunity costs associated with MAR systems using wells may be negligible.

The cost of water stored in a potable water ASR system is the marginal cost to abstract and treat the additional recharged water by a water treatment plant, rather than the average production cost or the price charged to customers. Average water costs includes labor, depreciated capital costs, and finances costs (*i.e.*, sunk costs), which would be incurred whether or not the additional water was treated. Local water utilities may obtain water from wholesaler on a take-or-pay basis, in which case they pay for water not used during low demand periods. Hence, there may be a strong financial incentive to store water during low demand periods as the utility is paying for it anyways [34]. In the case of a take-or-pay contract situation, the cost of water would be considered a sunk cost if the water would still be paid for if not used.

The storage space in an aquifer is another potential cost, which is rarely priced in accordance with its scarcity value [36]. Inasmuch as MAR is in its initial stage of development in many areas, there is a low demand for storage space, and it thus has minimal monetary value. However, if MAR implementation locally increases and a scarcity of aquifer storage space with suitable hydrogeologic conditions develops, then one can envision the cost of storage space becoming a significant component of CBA.

5. Benefits of MAR Systems

Water has an economic value only when its supply is scarce relative to its demand. Scarce water takes on value because many users compete for it [20]. The benefits of MAR systems are either additional water being available in times of scarcity, improvement in water quality, or a combination of both. Recharge of water can create a new freshwater resource, such as occurs in some ASR systems in which freshwater is emplaced in a brackish aquifer. MAR can also provide benefits by adding water to storage in an aquifer and thus stabilizing or increasing water levels. The total economic value of the recharged water includes its abstraction value plus *in-situ* (non-use) values derived from groundwater being in place.

Economic value is measured on the basis of substitutability, which can be expressed in terms of willingness to pay (WTP) and willingness to accept compensation (WTA) [29]. WTP is the amount someone would be willing to pay rather than do without a good or service. WTA is the minimum amount of money someone would require to voluntarily forgo a good or service. WTP and WTA may not be the same for a given good. Individuals tend to demand considerably greater monetary compensation to give up things that they already possess than they are willing to pay to acquire the same exact items. WTP is also constrained by a person's income in that wealthy people can afford and may thus be willing to pay more for a good or services than would poor people. The economic value to society of a good or service is the aggregate of the WTP of all individuals.

The economic value of water is not a fixed, inherent attribute of a good or service, but rather depends upon time, circumstances, and individual preferences [8]. The scarcity value of water changes with time, with its value increasing during times of decreased supply or increased demand. An important benefit of groundwater, whether placed through natural or enhanced recharge, is as a buffer against variation in surface water or other supplies [8]. Indeed, several studies have demonstrated that the greatest economic benefit of groundwater lies in the stabilizing of water supplies and avoidance of the economic impacts of shortages [37–41]. Surface freshwater flows should be the first source of water used, because they may otherwise be lost if not used when available. Fresh groundwater should optimally be reserved for strategic use in coping with water scarcity. MAR can enhance the ability of groundwater to play a stabilisation role by increasing the available supply of groundwater. Where global climate changes result in locally drier conditions, or a more viable water supply, then water stored in MAR systems would have an even greater value in the future, which needs to be considered in economic analyses.

A fundamental challenge with quantifying the economic benefits of water projects is that there is seldom a free market with respect to water and observed prices do not exist or fail to reflect its social value [42,43]. Often in both developed and developing countries, subsidization is common where water users do not pay the full cost of the construction and operation of the systems through water rates. Construction costs may have been paid for, at least in part, through general government revenues.

Water utilities are essentially monopolies and consequently price regulation is usually applied to protect the public. Publically owned utilities are usually either under direct governmental control or have an elected board. Privately owned utilities are commonly regulated by a governmental agency that has the authority to approve or deny rate increases. For publically owned water utilities, rates are typically determined to generate sufficient revenues to cover operation and maintenance (O&M) expenses, debt service payments, and capital expenditures financed by rates (as opposed to debt and governmental contributions and subsides). Pricing for privately owned utilities is commonly based on a "cost of service" approach, whereby rates are set to generate sufficient revenues to cover O&M expenses, depreciation, taxes (and tax equivalents) and an approved return on base rate.

From an economic perspective, consumers of water should actually pay the marginal cost of water (*i.e.*, the cost to obtain additional supplies) rather than the average cost [44], which is seldom the case. As is often the case for alternative water supply projects of water utilities, the marginal revenues from the additional supplies are less than the marginal costs, and the system is paid for by revenues from the sale of all water, both new alternative supplies and existing conventional supplies.

In developed countries, the price of water represents a small fraction of the household budgets and is usually given little thought. Water is provided at a much lower cost than what the consumer is willing to pay. The price that consumers pay for water can never exceed and seldom approaches the price that they would be willing to pay rather than go without, so the economic benefits derived from the use of water typically exceed the purchase price [20]. In economic terms, utility customers enjoy a substantial consumer surplus in that the value of the water they receive (in turns of WTP) exceeds the price that they pay for the water.

As a result of the consumer surplus, municipal water demand functions show a low elasticity. Rising prices over time may not significantly lower demands, particularly if real incomes are also rising [42]. Some uses are of great necessity to consumers (e.g., potable use, cooking) and there are no practical substitutes. At its limit, as supply approaches zero, the marginal value of water approaches infinity [42]. For example, strategic storage ASR systems are in various stages of development in some Middle Eastern countries that are highly dependent on desalination for the water supply [11]. In the event of a catastrophic disruption of the desalination facilities, due to a natural event, accident or war, millions of people could be without a water supply. The value of a strategic water supply to meet potable demands in an extreme emergency is inestimable [2], even though the probability of such an event is remote. There is thus a low probability that the strategic storage ASR systems could provide enormous benefits. However, placing a meaningful monetary value on the benefits of avoiding a very low probability catastrophic event is very difficult, because there are no precedents.

Since water is rarely priced at a market-determined scarcity value, comprehensive evaluation of MAR schemes require alternative nonmarket valuation methods [35,43,45]. Shadow pricing is typically used in which values are assigned or observed prices are adjusted to correspond to prices that would prevail in a competitive market. Shadow pricing is required, for example, to incorporate environmental costs and benefits in CBA of water projects. Some of the common methods to calculate or estimate the benefits of the water that might be supplied or treated by MAR projects are summarized below (Table 1).

Table 1. Methods to monetize benefits of managed aquifer recharge (MAR) systems.

Method	**Description**
Market prices	Value of water determined by actual prices set by willing buyers and sellers in a competitive market.
Alternative cost	Value of water storage or treatment is determined from the cost of the least expensive alternative that provides comparable benefits.
Value marginal product	The value of water is quantified from the marginal productivity of water, *i.e.*, the extra value of output that can be obtained from additional applications of water.
Contingent value	Survey-based methods to determine an individual's willingness to pay or willingness to accept compensation for a good or service.
Hedonic property value	Value of water is inferred from market transactions (e.g., real estate sales) that are linked to the value of water.
Defensive behavior	Value of a safe and reliable water supply can be estimated from expenditures to avoid exposure to unsafe water.
Damage cost	Value of water is estimated from damage costs avoided, such as health impacts or drought damage.
In-situ groundwater value	MAR system value is estimated from costs avoided resulting from groundwater being in place, such as pumping and land subsidence costs.

5.1. Market Prices

Quantification of the value of water is most straightforward where water is sold in a free market. Much has been written over the past two decades on the merits of free water markets as a means of promoting efficient use of water through pricing mechanisms. The principal objections to an entirely free water market system stems largely from the recognition that water is also a social good and that water trading can have significant third party effects (*i.e.*, externalities).

Market pricing systems result in water being allocated to where it results in the greatest net economic returns. The value of water can be determined from direct observations of transactions between willing buyers and sellers [45]. The spot market price under conditions at a given time is a direct measure of WTP. The limitation of using market pricing to determine the value of water is that there are few unfettered markets and that in the absence of a long-term time series of observations, the method may be of limited value for long-term planning purposes [45].

There are very few instances where free market trading prices have been use to quantify the benefits of MAR projects. One example is an evaluation of MAR in the Murrumbidgee region of New South Wales, Australia, in which the value of water was determined using temporary water trading prices (AU$450/ML) during a drought [46]. The spot market price for water will vary depending upon climatic conditions. Stochastic modeling of rainfall, water scarcity, and thus value of water, might be used to estimate potential future revenues from the sale of water over the operational life of a MAR system.

5.2. Alternative Cost Method

The alternative cost method is based on the notion that the maximum WTP for a good or service is not greater than the cost of providing that good or service through some other process or technology. The gross benefit of a project is considered to be the cost of the next higher cost alternative. The costs and benefits of MAR and other water projects would be considered relative to other water management options that would achieve the same goals [4–6,45,47]. The alternative cost method is similar to cost-effectiveness analysis in that it does not involve quantification of benefits for each project, which are considered to be constant for all options.

MAR systems with a storage goal can be compared against other options in terms of the unit cost of water recovered or delivered. Where the goal of the system is long-term storage, MAR systems could also be evaluated against other options in terms of the cost per unit storage capacity, with consideration given to recoverability. The alternative cost method is also appropriate for evaluation of MAR projects with a primary water treatment goal. The cost of systems that take advantage of natural vadose zone and aquifer treatment processes can be compared to the costs of alternative engineered solutions that provide the same water quality improvements

A basic problem with the use of the alternative cost method is that a more expensive alternative can always be conceived, which would produce an inflated estimated project benefit [45]. The analysis should demonstrate that the alternative project might actually be built. It is misleading to compare the cost of a MAR project against that of a much more expensive alternative that would never be built. For example, a MAR project to be used for irrigation water supply would be substantially less expensive than a seawater desalination plant built for that same purpose. However, this would be a misleading comparison as the latter would not likely be built, because of the great expense of the desalinated water relative to the value of irrigated crops.

The alternative cost method is commonly used to evaluate water supply projects in which additional water storage capacity or peak demand period water supply are required. For example, potable water demand in South Florida is greatest during the winter and spring dry season, which also coincides with the peak in tourism and seasonal resident population. Permitting of additional fresh groundwater withdrawals is generally no longer possible. The widespread implementation of ASR in Florida starting in the late 1990's was driven by its being the least expensive option to meet seasonal peak water demands [48]. ASR is a less expensive option than the next less expensive option, which is the construction of brackish groundwater desalination capacity that would not be needed (and would thus be idle) for a large part of the year.

5.3. Value Marginal Product and Residual Methods

The value marginal product (VMP) method considers the marginal change in the total value of product with a change in input. The value of water is quantified from the marginal productivity of water, which is the extra value of output that can be obtained from additional applications of water [34,49]. With respect to irrigation, the value of water is the change in income with and without an irrigation project, which is a function of increase in crop yield and crop prices. The marginal productivity of water can be calculated from crop-water production functions, which are empirical functions of crop yield *versus* irrigated water applications [43,45]. The function may be either experimental or based on surveys of water users [45]. Production functions are often a function of numerous variables including soil type, fertility, temperature, rainfall, irrigation practices, crop type, and plant growth stage [20]. It can, therefore, be difficult to distill out the specific contribution of irrigation. The increase in yields attributable to irrigation can be alternatively estimated as the difference between irrigated and dryland farming, assuming all other factors being equal. The VMP for irrigation should not be mistaken for water productivity, which is usually defined as the total value of crops divided by the amount of water applied.

The residual method estimates the value of water as the remainder of net income after all other relevant costs are accounted for. The cost of all non-water inputs are deducted from the estimated total value of production. The residual method is most accurate where water constitutes a significant fraction of the value of the output [45,47]. The residual method can result in large potential errors where water is a relatively minor portion of the total value of the product [45]. The residual method tends to give higher estimated values than other methods and over estimates the value of water if other variables are not included in the analysis [45], which is referred to as the "omitted variable problem." Before and after comparisons (irrigated *versus* non-irrigated land) may ignore other variables that influence incomes [22]. There are also disagreements about whether or not and how to consider owned resources (versus contractual resources) such as land, capital, entrepreneurship, and management [45]. Land values can be obtained from rental and sales market.

Limited data are available on the marginal value of water in agriculture in general, and the reported values show a very wide range. Colby [43] reported estimated values of water in agriculture of USD4 to USD236 per acre foot (USD0.003/m^3 to 0.19/m^3) in the western United States. Hussain *et al.* [50] compiled more recent estimates of the value of agricultural water and documented that average values vary greatly across countries and regions, from as low as USD0.001/m^3 to 0.74/m^3.

The VMP has also been used to estimate the value of water in industrial uses. However, water costs are usually very often only a small fraction of total costs [42]. Water supply cost is thus a secondary decision. As water supply and wastewater disposal costs increase, recycling of water increases. However, scattered studies indicate that industrial water demand is quite inelastic [42].

VMP could be used to evaluate the environmental benefits of MAR, such as the restoration and protection of groundwater-dependent ecosystems, in a manner analogous to valuing water for irrigation use. The value of water would be related to the marginal increase in ecosystem services provided by the additional water. The difficult and contentious issue is monetizing ecosystem services. For example, the impacts of an aquifer recharge scheme on spring flows and wetland hydration can be determined through monitoring and modeling. Assigning a monetary value to the benefits of the increased spring flows and wetland hydration has a much greater uncertainty.

5.4. Contingent Value Methods

Contingent value methods (CVM), which are also referred to as expressed preference approaches, are survey-based methods used to determine individuals' WTP or WTA for a good or service. The methods involve asking people directly what they would be willing to pay contingent on some hypothetical change in the future state of the world. With respect to environmental issues, a description of conditions simulating a hypothetical market is presented, to which respondents are asked to express their WTP or WTA for existing or potential conditions not registered in any market [45]. A hypothetical application of the CVM to a MAR project is

> "*Your local water utility has completed an investigation of different options to address the current annual water shortages during the summer dry season. The shortages result in restrictions that curtail outdoors water uses, such as lawn and garden watering. The results of the investigation indicate that a managed aquifer recharge system could be constructed that would provide an additional 1 million m^3 of water in the summer. The additional water would reduce the need for water use restrictions to less than once in every ten years. Would you be willing to pay an extra $2 per month on your water bill to pay for the MAR system?*"

The cost of the system could be expressed as a discrete choice or evaluated using an iterative bidding process. In the former case, which is referred to as the dichotomous choice or referendum method, a respondent is asked only whether or not they would be willing to pay a specified amount in a specified manner as a "take it or leave it" decision. Iterative bidding processes involve starting with an initial price and then adjusting it upwards or downwards to determine the maximum WTP. For example, if a respondent indicated that they would be willing to pay an additional $2 per month for the MAR system, then they might next be asked if they would be willing to pay $3 per month, and so on, until they indicated no. Conversely, if the response to the initial price is no, then the price would be incrementally reduced until the respondent indicated yes. It has been documented that the initial bid price used can impact survey results.

CVM are subject to a number of potential biases, which has been discussed at great length in the economics literature and was reviewed with respect to CBA and the value of water and the environment by Boardman *et al.* [22], the National Research Council [8] and Young [45]. A basic limitation of CVM is that people's statements about their preferences may not reveal their true preferences and actual behavior, because statement of a WTP does not involve an actual payment obligation. Due to the hypothetical nature of the process, declared intentions may not be accurate guides as to actual future behavior. The biases could either be unintentional or a strategic behavior. As an example of the latter, someone in favor of a water project may intentionally give an excessively high WTP in order to try to influence the survey results. Similarly, respondents may give a low WTP for a project with the hope that in by doing so they may keep future water rates lower. Strategic behavior may be detected as outliers. Sample bias and non-response biases occur when the respondents do not represent all the stakeholders for a project. Interviewer and neutrality biases occur when the respondent perceives that a particular response is preferred by the interviewer or when the question is framed in a manner that is not neutral.

5.5. Hedonic Property Value Method

The hedonic property value method is a revealed preference method in which the valuation of non-market goods and attributes is determined by observing market behavior. Expenditures for market goods are linked to the value of nonmarket goods or attributes. The method assumes that an increment in price due to an increase in one characteristic will equal a buyer's WTP for the characteristic as well as the seller's marginal cost of producing that characteristic [45]. The hedonic property value method requires market data and assumes that market participants are able to recognize differences in characteristics. It is commonly based on real estate transactions. A commonly given example is that the value of a living next to a lake can be determined by comparing the sales price of homes with and without a lakefront.

With respect to water, the value of groundwater for irrigation use can be estimated from the difference in price of a unit of land with and without a groundwater right or supply. The hedonic property value method assumes that all other variables are equal. However, with respect to water rights in the western United States, the value of water rights depends upon their security (seniority), water quality, and location of use [43].

5.6. Defensive Behavior and Damage Cost Methods

The defensive behavior method is based on the WTP to avoid adverse environmental effects [45]. For example, the value of safe drinking water can be estimated from the amount of money that people would pay to avoid exposure to contaminants, such as by purchasing bottled water. The premise of the method is that a rational person will adopt defensive behavior as long as the value of the damage avoided is greater than the cost of the defensive step.

Benefits of MAR systems can be evaluated in terms of damage costs avoided. For example, the benefits of bank filtration systems to provide safer drinking water in rural areas of developing countries can be evaluated in terms of the costs of disease avoided. The costs of disease includes health care expenditures, lost wages and labor (e.g., farmers not be able to tend their fields), and human suffering and premature death. A challenge in evaluating the benefits of water supply and sanitation systems is monetizing the value of a human life and the effects of sickness [31]. An approach taken to evaluate the latter is to use the product of days of work lost and local wages. Similarly, a benefit of water supply projects may be a reduction in the labor required to obtain water, which is a large burden on women and school-age children in areas of some developing countries.

The benefits of an MAR system for irrigation water supply can similarly be estimated from the costs of crop damage during droughts that would be avoided as a result of the stored water. Such an evaluation would require a statistical (probabilistic) analysis of drought frequency and intensity, associated crop damage, and the economic value of lost crops.

5.7. In-Situ Values of Groundwater and MAR

In-situ values include a variety of benefits associated with additional groundwater being in place in an aquifer (*i.e.*, higher groundwater levels), as opposed to benefits associated with the abstraction and use of groundwater. *In-situ* benefits are the objectives of systems that involve aquifer recharge without recovery. Reduction in pumping costs is an often cited example of an *in-situ* value that would be a benefit of MAR. Higher groundwater levels result in less energy required to pump water and thus cost savings. The economic value of an MAR system with respect to pumping costs is a function of the change in water level, decrease in energy required to pump the water, and the energy cost. Pumping cost benefits of an MAR project in a given year (C_t) are estimated as [51]:

$$C_t = P_t L_t W_f \quad (2)$$

where P_t is the pumping cost per volume of water per unit of lift per year; L_t is the cumulative average lift change per unit area (ft); and W_t is the amount of water pumped within the affected area without recharge.

Reichard and Bredehoeft [52,53] performed an economic analysis of the Santa Clara Valley, California, aquifer recharge system. The system uses infiltration basins to recharge a heavily used alluvial aquifer system. A calibrated groundwater flow model was developed and used to calculate the hydraulic effects of the on-going aquifer recharge system. The energy savings was calculated from the modeled increase in heads, annual abstraction volumes, the energy requirements to lift an 1 acre-foot of water (1232 m^3) 1 foot (0.3 M) using a 100% efficient pump, and an average pump efficiency. The energy requirement for a 100% efficient pump is 1.02 KwH to lift 1 acre acre-ft one foot, which is equivalent to 2.71 KwH to lift 1000 m^3 of water 1 m. The benefits of reduced subsidence per foot of drawdown avoided were calculated using an estimate of the economic impacts of historic subsidence divided by the historic drawdown [52,53].

6. Risk and Uncertainty in CBAs

Perhaps the most neglected aspect of the economics of MAR is addressing risk and uncertainity in CBAs. Risk and uncertainty are often considered synonymous. However, the term "risk" implies that there is some idea of the probability of various events [24,27]. Uncertainty implies that the probability of future events is not known. Although there are without doubt risks and uncertainty associated with the implementation of MAR, as evidenced by some failed or underperforming systems, the existence of risk and uncertainty in projects is seldom acknowledged [11], much less explicitly incorporated into CBAs.

The principle risk and uncertainty associated with MAR systems is that they may fail to meet performance objectives. System performance depends local upon hydrogeologic conditions, which may turn out to be unfavorable for achieving system goals. Adverse results include:

- Recharge may not result in anticipated changes in aquifer water levels;
- Anticipated additional water may not be available when needed (*i.e.*, system has a poor recovery efficiency;
- Unexpected water quality changes due to fluid-rock interactions (e.g., leaching of arsenic into stored water);
- Well performance problems (e.g., low well capacities, well or formation clogging);
- Excessive infiltration basin clogging;
- Water treatment goals are not achieved; and
- Anticipated demand for water (and associated revenues) may not be realized.

For example, the USD150 million dollar Las Posas Basin ASR system in California is considered a failure as it did not achieve water storage goals [54]. The recharge of an enormous volume of water over operational life of the systems did not result in a corresponding increase in aquifer water levels, and thus the water that was "banked" on paper could never be recovered [11].

Some adverse results may be remedied at an additional cost and thus the systems may still be viable. Arsenic leaching and excessive well clogging may be avoided, for example, by pre-treating the recharged water. The additional costs would result in projects having lesser NPVs, but still being economically viable if the benefits are great enough. Some failed ASR systems provided eventual (salvage) value when the wells were put to alternative uses. For example, the Bonita Springs Utilities (Southwest Florida) potable water ASR system encountered hydrogeological conditions that were unsuitable for ASR. A very high degree of aquifer heterogeneity resulted in excessive migration and mixing of injected water and native groundwater [11]. The ASR well was subsequently put to use as the most productive brackish water supply well for their desalination system.

The main source of risk associated with MAR systems stem from a natural groundwater system being used whose hydraulic and geochemical properties can never be fully characterized. The possiblity thus exists that unexpected adverse conditions may be encountered. The risks associated with MAR systems can be reduced, but never entirely eliminated, through high-quality and more-detailed aquifer characterization [11]. Post-audits of both successful and unsuccessful systems can provide valuable lessons that can be a guide for future implementation of MAR [11].

It would clearly be negligent to assume in any CBA that a 100% favorable result will be obtained, when there is a real potential for poor results. Risk and uncertainty can be incorporated into CBA through an expected value analysis, as reviewed by Boardman *et al.* [22]. The future is characterized in terms of a number of distinct contingencies. To evaluate risks, one has to be able to assign probabilities to the occurrence of each possible contingency. Modeling of risk and uncertainty begins with a set of contingencies that are mutually exclusive and capture the full range of likely variations in the costs and benefits of a project or policy.

For example, the net economic benefits of water storage systems vary with the amount of rainfall (and thus demand for water) and the performance of the system (*i.e.*, how much additional water could be recovered when needed). Rainfall also effects natural recharge (thus aquifer water levels and storage space) and the amount of water available for recharge. The average net benefits can be calculated based on the probabilities of different rainfalls and probabilities of different recovery volumes over the operational life of the system. The basic procedure is to identify all potential contingencies and to assign a probability to each. The sum of probabilities for all of the contingencies is equal to one. Probability of each contingency can be based on historic experience (e.g., rainfall data) or subjective opinions of experts. The expected net benefits (ENB) are calculated as:

$$ENB = \sum P_i(B_i - C_i) \quad (3)$$

where P_i = probability of contingency "i"; and B_i and C_i are the present value of the benefits and costs of contingency "i". Not considering risk and uncertainty biases CBAs by increasing expected benefits.

Evaluation of expected net benefits is generally reasonable when there is a pooling of risk, which will make the actual realized values and costs close to the expected values [22]. A limitation of the net expected value method is that it does not capture relevant concerns about extreme negative outcomes [24], particularly where risk is unpooled. Individuals and organizations are often averse to bad outcomes. A low probability risk of a completely failed system may be unacceptable to a small utility with limited resources. The ENB can be weighted to give higher weight to negative outcomes, in the case of a risk-averse decision maker.

Risk analysis can be performed using Monte Carlos analysis, which involves the following main steps [22]:

(1) Specification of probability distributions for all important uncertain quantitative assumptions;
(2) Execution of a trial by taking random values drawn from the distribution for each parameter to arrive at a set of specific values for computing realized net benefits; and
(3) Repetition of the trial numerous times to produce a large number of realizations of net benefits.

The results of all the realizations are used to determine the probability distribution of net benefits.

Risk and uncertainty will also change as a project proceeds. Large MAR projects are implemented in a phased manner. Data collected during an exploratory well program and pilot testing reduce risk and uncertainty and should be used to re-evaluate project feasibility [11]. An updated CBA can thus be performed before the decision is made to construct a full-scale system.

7. Finance of MAR Projects

MAR projects are primarily funded in four main manners [2]:

- Revenues from the sale of water;
- Direct assessment (pump tax or assessment based on volume of groundwater used);
- Ad valorem tax on real property; and
- General tax revenues.

MAR projects in developing countries may also be funded by external sources, such as international agencies and non-governmental organizations (NGOs). Water users, the primary beneficiaries of projects, should ideally have responsibility for financing projects, through either water rates, direct assessments or ad valorem taxes. Small-scale projects may be constructed through self labor or some sort of cooperative structure. However, the beneficiaries of economically feasible projects may not have financial resources for projects. Construction costs are up front, while benefits occur in the future. The financial constraints are particularly acute in poor areas of developing countries.

The finance of large water supply and storage projects is often controversial because of a dichotomy between the primary beneficiaries of a project and parties that pay for a project. The dichotomy may work in both directions. Projects are often subsidized in that the direct beneficiaries do not fully pay for a project. Governmental and non-governmental agencies may subsidize MAR projects to vary degrees through:

- Projects financed through general revenues or governmental borrowing;
- Grants or low or no interest loans for utilities; and
- Projects entirely funded and constructed by a governmental agency.

Government projects are often favored where concentrated benefits are received by an influential target group and costs are shared in a diffuse manner by society as a whole [22]. Subsidies are commonly justified in terms of secondary benefits. Agricultural projects, for example, support agricultural communities, not just farmers. Subsidies could be justified to achieve societal goals, such as equity (*i.e.*, access of water to all) and food security. Subsidies are justified when the price of a good does not fully reflect its value [45], but can have the adverse impact of encouraging use in quantities greater than the economically efficient quantity.

On the other hand, the operation of a MAR system may provide broader societal and environmental benefits, but the costs may be borne entirely by the system owner (e.g., local water utility and customers). A project may be economically efficient in terms of its total benefits and costs, but not feasible to the owner, because the owner will not receive sufficient personal benefits to cover costs. In other words, there is not an adequate "business case" to justify the investment in MAR. In this case, some sort of governmental subsidy or other means of financial support from more (ideally all) beneficiaries may be justified.

The issue of finance is well illustrated by the Las Vegas, Nevada (USA) aquifer recharge system, for which Donovan *et al.* [55] provided a cost-benefit analysis for non-municipal water users. The Las Vegas aquifer system recharges an historically overdrafted alluvial aquifer with seasonally available excess treated surface (Colorado River) water, with the primary goals of increasing available water resources, slowing or reducing the decline in water levels, and reducing the rate of land subsidence. The recharge is performed using injection wells and water is abstracted by municipal users and non-municipal water users using privately owned on-site wells.

The net benefits of the system to non-municipal users were calculated to be about USD700 per 1230 m^3/year, which is largely from cost savings from deferment or elimination of the need to rehabilitate and replace wells. Well rehabilitation would consist of deepening wells and/or lowering pumps in response to a continuing decline of aquifer water levels that would otherwise occur without the recharge. There are additional minor savings from reduced energy consumption. Non-municipal users were receiving these benefits for free. The solution was to implement a groundwater management program (GMP) in which non-municipal users are charged on either a per well or permitted water use rate basis in order to support the system.

8. Discussion

Economic analysis of MAR systems are inherently project specific, depending upon the type of system, performance objectives, local hydrological and physical conditions, planned uses of the recovered and stored water, and alternative water supply and treatment options. General and system-specific feasibility is dictated by their benefits, which is determined by the value of water. ASR and other forms of MAR are usually economically feasible (*i.e.*, have a positive NPV), where water is used for municipal (potable) use in water scarce regions, provided that local hydrogeologic conditions are favorable for achieving system performance goals.

Multiple approaches may be appropriate to evaluate the economics of MAR projects. Consider, for example, a riverbank filtration (RBF) system to improve potable water quality in a developing country. The economic viability of the project could be considered using cost-effectiveness, by comparison of the costs of the RBF system with other options that would provide comparable water quality benefits. Alternatively, a CBA could be performed in which the present value of the costs of the systems is compared to the present value of the benefits provided. Expected benefits might be a reduction in sickness and premature mortality that are the result of ingestion of or contact with water-borne pathogens. Proposed systems should be economically viable using both approaches.

The actual costs of MAR systems in terms of total costs and cost per volume of recovered or treated water are highly system-specific. In general, MAR systems provide the greatest benefits where the water is put to a high value use and alternative, inexpensive options are not available. Potable water ASR in South Florida provides a good example of some of the economic issues associated with MAR for a high value use. ASR has been implemented primarily to meet peaks in demand during the winter and spring dry season. The current costs for brackish groundwater desalination (the least expensive alternative) are commonly now in the USD0.30/m^3 to 0.60/m^3 range, which is based on full-time operation of the plants. The costs of desalinated water from facilities constructed only to meet peaks in demand would be substantially greater than the above estimates (approximately USD0.70/m^3 to 1.50/m^3), because the large annual depreciated construction and fixed operational costs for a desalination system would be divided by a relatively small seasonal production volume, resulting in higher unit costs. Desalination costs would also depend upon whether an existing plant is expanded or a new plant is constructed, and the size of the plant and associated economy of scale.

There is a substantial economy of scale associated with wells. For example, doubling of the capacity of wells typically involves significantly less than a doubling in the cost of the well, wellhead, pump, and piping. The costs of regulatory compliance are also independent of well capacity. On the benefit side, cost per unit volume is directly proportional to the volume of water recovered, which is a function of system capacity, recovery efficiency, and demand (*i.e.*, amount of available water that is actually recovered). The annual cost for a 1 to 2 million gallons per day (3788 to 7576 m3/d) ASR system that is recovered for 90 days per year is on the order of USD0.30/m^3 to 0.60/m^3 in South Florida. The cost of ASR to meet peaks in potable water demand, therefore, can be 50% or less than the cost of brackish water desalination.

The economics of MAR for irrigation water supply are much more variable because of the wide range of monetary values of water associated with this use. The value of water for irrigation depends upon the crop type being grown, and is typically relatively low for cereal crops and greater for fruits and vegetables. The value of water in agriculture also depends upon local market prices for crops. A wide range of values has been presented for the value of water in agriculture with most being no more than USD0.001/m^3 to 0.79/m^3 [50]. Hence, MAR systems for agricultural water supply need to be low cost and passive (*i.e.*, do not require large amounts of energy and human intervention to operate). MAR methods most appropriate for irrigation water supply are systems that recharge untreated water (stormwater and flood water) using infiltration basins and ponds, and in-channel modifications (e.g., check dams).

Small-scale MAR systems for potable water supply are right-sized for some rural areas and developing countries. For example, production of water from riverbank filtration systems consisting of drilled or dug shallow wells located adjacent to a river can be a very cost-effective means to improve water quality with concomitant health benefits. Riverbank filtration has been demonstrated to be a less expensive option than conventional surface water intakes and filtration systems where local hydrogeologic conditions are favorable. One small-scale MAR application in India is the inexpensive retrofitting of existing tube wells to allow for aquifer recharge whenever excess rain or canal water is available [56]. The main cost elements are construction of a connecting channel to convey canal water and construction of a settling basin and filter tank [57]. A variety of other methods are employed in India to enhance recharge such as surface spreading using percolation tanks (ponds) and check dams constructed across or near streams, and drainage channels in order to impound runoff and retain it for a longer time to increase the opportunity time for recharge [58].

Managed aquifer recharge of recycled or reclaimed water can be a valuable water resources management tool as it may allow for more of this resource to be put to beneficial use and avoids the costs and environmental impacts of its disposal. For example, the primary economic benefit of a reclaimed water ASR system is Destin, Florida (USA), is that it is much less expensive there to store excess reclaimed water underground during periods when supplies exceed demands than to construct new disposal facilities due to limited land availability and regulatory and political objections to an offshore outfall [59]. The ASR system also has the important benefit of increasing the reliability of the reclaimed water supply, which makes potential customers more willing to commit to connecting to the reuse system. However, a widespread constraint on the implementation of reclaimed water ASR is that the water is often provided to customers at a low (and in some instances no) cost, so there is little financial incentive (benefits received) to invest in the systems, particularly where a low-cost disposal option is available.

An important area for additional research is the collection and analysis of accurate data on the economics of existing MAR systems. Data are needed on the construction and operational costs and benefits of the various types of systems and in different geographic locations. The conceptual framework exists for evaluation of the economics of MAR systems, but there is a paucity of hard data to perform meaningful cost-benefit analyses. The paucity of actual data on the economics of MAR systems, which demonstrates that their benefits exceed costs, is a continued impediment to the further implementation of the technology.

9. Conclusions

The economic feasibility of MAR can be evaluated using conventional CBA in which the NPV of system options are determined and compared against each other and other water storage and treatment options. The CBA process should be rigorous and consider all marginal costs and benefits, risks, and opportunity costs. The greatest uncertainty in CBA analysis of MAR relates to monetizing benefits, which ties into the more basic question of the value of water. In the absence of a free market-derived WTP price for water, shadow pricing is required to estimate project benefits, such alternative cost and value marginal product methods. A major deficiency of past economic analyses of MAR is the failure to consider risk, particularly the effect of possible system under-performance in reducing system benefits.

CBA of MAR systems is highly dependent on site-specific conditions. In general, systems are economically viable where the water is put to a high-value use, such as potable and some industrial and irrigation water supplies. MAR system for lower value irrigation water supply (e.g., cereal crops) should be low cost, passive systems. MAR systems should ideally be financed by the primary project beneficiaries. As is the case for many water projects in general, MAR projects are often subsidized when beneficiaries are unable or unwilling to pay the full costs. Finance of MAR can be particularly challenging in rural areas of developing countries where financial resources are limited and the construction costs have to be borne before benefits of the systems are realized.

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Conflicts of Interest

The author declares no conflict of interest.

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