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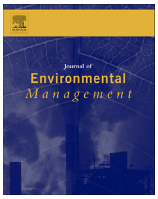

Research article

Application of natural resource valuation concepts for development of sustainable remediation plans for groundwater

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ABSTRACT

This paper explores the application of natural resource assessment and valuation procedures as a tool for developing groundwater remediation strategies that achieve the objectives for health and environmental protection, in balance with considerations of economic viability and conservation of natural resources. The natural resource assessment process, as applied under U.S. and international guidelines, entails characterization of groundwater contamination in terms of the pre-existing beneficial services of the impacted resource, the loss of these services caused by the contamination, and the measures and associated costs necessary to restore or replace the lost services. Under many regulatory programs, groundwater remediation objectives assume that the impacted groundwater may be used as a primary source of drinking water in the future, even if not presently in use. In combination with a regulatory preference for removal or treatment technologies, this assumed exposure, while protective of human health, can drive the remedy selection process toward remedies that may not be protective of the groundwater resource itself or of the other natural resources (energy, materials, chemicals, etc.) that may be consumed in the remediation effort. To achieve the same health and environmental protection goals under a sustainable remediation framework, natural resource assessment methods can be applied to restore the lost services and preserve the intact services of the groundwater so as to protect both current and future users of that resource. In this paper, we provide practical guidelines for use of natural resource assessment procedures in the remedy selection process and present a case study demonstrating the use of these protocols for development of sustainable remediation strategies.

1. Introduction

Sustainable remediation, as defined in current guidelines, entails coordination of the resource consumption of the remediation effort with the benefits achieved in terms of the economic viability, conservation of natural resources and biodiversity, and the enhancement of the quality of life in surrounding communities (ASTM, 2013; Ellis and Hadley, 2009; SURF, 2016). A key consideration in selection of a sustainable remedy at a given site is the loss of natural resource service caused by the contamination (AFCEE, 2009) and the ability of the remediation program to restore this service at a cost that is commensurate with the lost value. Environmental economists and regulatory authorities in the US (Desvousges, 2010; Dunford, 2004; Dunford and Locke, 2015) and abroad (Deloitte, 2013; UKEA, 2007) have reviewed methodologies for estimation of the economic value of groundwater and consideration of the lost value caused by contamination. Other authors have evaluated the evolving legal and regulatory policies related to assessment of groundwater resource damages and restoration of beneficial use (Dunn, 2008; Israel, 2015; Reed, 2014; Tolan, 2008).

However, under regulatory and technical guidelines for groundwater remediation, these resource assessment and valuation concepts have not commonly been integrated in the remedy selection process. In the US, under both the CERCLA and RCRA programs, the principal remedy selection factors (hereinafter referred to as “conventional remedy section criteria”) are long-term effectiveness and permanence; reduction of the toxicity, mobility, or volume of waste; short-term effectiveness; implementability; and cost, wherein cost is considered as a secondary criterion to compare “disproportionate costs” among remedy options (USEPA,

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1992, 1997, 2014, 2015). These regulatory programs incorporate a preference for treatment options (USEPA, 1992), which can drive the remedy toward chemical or physical modification of the impacted natural resource (e.g., groundwater), rather than containment or natural attenuation of the contaminants. In addition, many regulatory provisions specify that the remedy be completed in a "reasonable" timeframe (40 CFR §300.430(a)(1)(iii)(F)), without providing specific guidance on what constitutes "reasonable."

Parties seeking to encourage sustainable remediation have noted a deficiency in the remedy selection process with regard to the protection and efficient use of the groundwater resource:

> "*Current water quality standards require that treated groundwater quality be suitable for the intended reuse application. Although these regulations protect groundwater quality, they do not emphasize the beneficial reuse of the water that all too often is lost as a result of remediation activities.*" (SURF, 2013, p. 5).
>
> *When developing remedial action objectives and groundwater cleanup goals, the function and services provided by groundwater should be considered. Depending on the importance of groundwater in a particular area, regional factors such as geography, climate, local industry, and population drive the valuation of groundwater.*" (SURF, 2013, p. 13).

Other authors have noted the importance consideration of net environmental benefit in remedy selection (Raymond et al., 2009) and have reviewed methodologies for evaluating the positive and negative effects of the remedy on natural resource services (Fiorenza et al., 2009).

Remedial alternatives that, based on conventional remedy selection criteria (i.e., long-term effectiveness; reduction of the toxicity, mobility, or volume, etc.), are expected to provide equal protection to human health may nevertheless entail very different net effects on the services provided by the groundwater resource. Failure to consider the natural resource implications poses concern with regard to damage to the groundwater resource undergoing remediation, as well as investment, in terms of capital and resource consumption, that is disproportionate to the value of the impacted groundwater.

An example of such resource impacts is a groundwater pumping and treatment system that removes contaminants from the aquifer by flushing the impacted zone with clean water drawn from the surrounding area. In the course of this process, this remediation system may extract and contaminate a groundwater volume that is orders of magnitude greater than the volume that would have been affected in the absence of remediation. Similarly, under the commonly used regulatory definition of "potentially usable" groundwater (i.e., groundwater with a Total Dissolved Solid content $<$ 10,000 ppm from a well capable of producing more than 500 L per day; 40 CFR §144.3), a relatively low-value groundwater unit (unused, low-yield and/or brackish) and a relatively high-value groundwater unit (in use, high-yield, and fresh) may warrant equivalent remediation efforts - even though the high-quality unit supports a significant user population and the low-value unit supports no users and at best could be considered an optional, back-up supply.

Subject to applicable environmental regulations, both groundwater units may require remediation, as needed to protect human health and the environment; however, the timeframe and level of resources applied to the low-value vs. the high-value groundwater unit would reasonably be expected to be quite different. Conventional remedy selection criteria do not provide guidance with regard to distinction between high-value and low-value groundwater or to consideration of either resource value or consumption in development of the remedial strategy.

A number of regulatory authorities in the US and abroad have adopted "non-groundwater use" provisions that allow affected groundwater to remain in place in excess of drinking water standards within aquifers that are not current sources of drinking water, subject to certain technical specifications and institutional controls. Examples include the Municipal Settings Designation in Texas (Texas Health and Safety Code Chapter 361 Subchapter W), the Model Groundwater Ordinance in Illinois (35 Ill. Adm. Code 742.1015), the Groundwater Use Restriction in Colorado (CDPHE, 2015), and the Groundwater Classification Exception Area in New Jersey (N.J.A.C. 7:9C-1.6). Similar provisions are provided in Catchment Abstraction Management Strategies in the United Kingdom (UKEA, 2013), in Environmental Protection Orders in Alberta, Canada (Alberta Environmental Protection and Enhancement Act Provision 156), and in Groundwater Quality Restricted Use Zones in Victoria, Australia (EPA, 2014).

For sites meeting these non-use provisions, remediation is not required for groundwater resources that would be characterized as low value, based upon their location and the presence of alternative, higher-quality water supplies. However, for sites that do not qualify for these exclusions or are located in jurisdictions where such provisions are not available, concerns remain regarding the net effect of the remedy on the services provided by the groundwater and other natural resources.

Guidelines for assessment of groundwater resource value and damage are addressed in various US and international guidelines (43 CFR Part 11; EU Directive 2004/35/CE; Deloitte, 2013; Desvousges, 2010; Dunford, 2004; Dunford and Locke, 2015; UKEA, 2007). Under these systems, the impacted groundwater resource is evaluated with regard to its baseline services to humans and the environment, the loss of service caused by the contamination, and the measures needed to restore and/or compensate for the lost service without degrading the other services that are still provided by the groundwater. Consequently, as a supplement to conventional remedy selection criteria, natural resource assessment protocols may serve as a systematic process for incorporating sustainability objectives into remedy selection and design.

In this paper, we apply groundwater resource assessment and valuation methods, as defined in US and international guidelines, as a tool for evaluating the relative sustainability of alternative remedies in terms of net resource benefits and the consistency of the timing and resource consumption of the remedy with the demand for the impaired groundwater. We present a step-wise process for applying resource assessment concepts to the remedy selection process and provide case study examples for development of remediation strategies that are protective of a groundwater resource and the users of that resource, while meeting the objectives of sustainability.

2. Technical background on natural resource assessment protocols for groundwater

In the U.S., the concept of liability for damage to natural resources was first codified under the Trans-Alaska Pipeline Authorization Act (TAPAA) of 1973 and the Deepwater Port Act (DPA) of 1974, which required owners or operators of pipelines or marine vessels to compensate the public official serving as trustee of the damaged natural resource (Lee and Bridgen, 2014). These provisions and the concept of "natural resource damage" were expanded under the federal Clean Water Act, Comprehensive Environmental Response, Compensation and Liability Act, and the Oil Pollution Act. Regulations for implementing NRDA have been promulgated by the U.S. Department of Interior (DOI) in 43 CFR Part

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11, which provides detailed technical guidelines for damage assessments due to impacts of hazardous substances on various environmental media, including groundwater. In addition, the National Oceanic and Atmospheric Administration (NOAA) issued NRDA regulations in 15 CFR Chapter 990 Subchapter E, which specifically address oil impacts subject to OPA.

In the United Kingdom (UK), in the context of the Water Framework Directive, the Environmental Agency has issued comparable guidelines for assessing the value of a groundwater resource as a component of a cost-benefit analysis for groundwater resource protection and remediation (UKEA, 2007). The European Union (EU) Directive 2004/35/CE sets forth similar provisions for assessment, compensation, and remediation of damages to natural resources caused by polluting activities.

Guidelines for assessment of groundwater resource value and damage are addressed in various US and international guidelines (43 CFR Part 11; EU Directive 2004/35/CE; Deloitte, 2013; Desvousges, 2010; Dunford and Locke, 2015; UKEA, 2007). Under US guidelines, the assessment process entails characterization of three principal elements:

a) The *injury* to the resource, where the “injury” is a change in the chemical composition, yield, or discharge of a groundwater aquifer;
b) The *loss of service* associated with that injury, where “service” pertains to the beneficial use of the groundwater by human users or the ecosystem and/or other in-place services, such as prevention of ground subsidence; and
c) The *damage* or the monetary value of the lost or impaired service caused by the injury.

The economic value of the “damage” is commonly considered to be the sum of 1) the costs of restoration of the lost service and 2) the compensable value of the lost service until such time as restoration is achieved (43 CFR §11.83). Groundwater valuation guidelines issued by the UK Environment Agency follow a similar process, considering the change in the quality or quantity of the groundwater resource and the net effect on the benefits provided to the users of that resource (UKEA, 2007).

Under both the US and international programs, a key concept is that “damage” refers to the change in the pre-existing (i.e., “baseline”) services provided by the resource – not the change in the baseline chemistry of the groundwater. The 2008 amendment to the US Department of Interior (DOI) regulation clarified this point, stating “the measure of damages is the cost of (1) restoring or rehabilitating the injured natural resources to a condition where they can provide the level of services available at baseline, OR (2) replacing and/or acquiring equivalent natural resources capable of providing such services” (USDOI, 2008, 73 FR 57261, October 2, 2008). For example, groundwater that has been impacted by chemicals at concentrations at or below drinking water criteria has not been injured or damaged as a drinking water resource.

Legal analysts (Tolan, 2008) find this concept to be reflected in rulings on cases such as the State of New Mexico vs. General Electric et al. (U.S. District Court for the District of New Mexico, Case Nos. CV 99–1254 BS and CV 99–1118 BSJ), in which the US federal court found that the damage caused by contamination of a drinking water aquifer must be evaluated as the cost of replacement of the lost water service, which could be economically achieved by wellhead treatment, relocation of a supply well, and/or use of an alternate water supply. (Disclosure: In this New Mexico case, the principal author of our paper served as a technical expert on groundwater use, contamination, and restoration.) Furthermore, if a groundwater unit loses value as a drinking water supply, it may nevertheless retain value for other services, such as irrigation, fire control, etc., such that the damage is the net loss of value attached to drinking water compared to other uses – a consideration incorporated in both US and international guidelines (EU Directive 2004/35/CE; Tolan, 2008; UKEA, 2007). Finally, under US rules, in order to make a claim for damage, the lost beneficial use of the groundwater must not be speculative; rather, there must be a “committed use” demonstrated by a formal plan to use the groundwater for the service (e.g., drinking water) alleged to have been lost (43 CFR 11.84(b)(2)).

3. Consideration of lost groundwater service and value in remedy selection

As a supplement to conventional remedy selection criteria, groundwater valuation concepts can be used to: i) characterize the baseline services of an impacted groundwater unit, ii) define remediation objectives directed toward replacement of that lost service, protection of its users, and preservation of other unimpaired uses, and iii) select remediation methods that restore the lost service in a manner that is commensurate with its value.

3.1. Characterization of baseline services

Guidelines for characterization of the baseline service of a groundwater unit commonly recognize four general categories of use, which can be expressed as follows:

1) *Extractive:* Pumping and use of the groundwater as a water supply for drinking, irrigation, industrial purposes, etc.
2) *Non-Extractive/Discharge:* Natural discharge of groundwater to surface water so as to sustain wetlands, aquatic ecosystems, recreational uses of the surface water body, or a surface water supply.
3) *Non-Extractive/In-Situ Stock:* The in-place functions of groundwater for water storage, prevention ground surface subsidence, prevention of seawater intrusion into freshwater aquifers, or, when appropriate, protection of usable water resources by providing a reservoir for safe disposal of waste liquids.
4) *Option Value:* Service as a future, back-up water supply.

Table 1 provides a checklist of the possible beneficial services provided by a groundwater unit prior to impact by chemical contaminants. The relevant extractive uses of the groundwater can be characterized based upon its chemical suitability for various applications, using accepted water quality classification criteria such as Total Dissolved Solids (TDS) content as well as the water yield needed to meet the specified use (e.g., domestic vs. public water supply).

Groundwater units that are not currently providing service for extractive uses, due either to availability of a superior and/or more economical water supply, relatively poor quality or yield, or lack of demand, may nevertheless provide an *option value* as a back-up or reserve water supply. For example, under USEPA guidelines, groundwater units that are not currently being used, are in areas served by public water supplies, but exhibit a Total Dissolved Solid (TDS) content < 10,000 ppm and can produce more than 500 L per day from a well are considered potentially usable as drinking water by a hypothetical future user. However, this hypothetical future use corresponds to an option value, rather than the higher value associated with an aquifer under current extractive use. This distinction among the services provided by various groundwater sources provides a basis for weighing the appropriate resource investment and timing of the remedial action.

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Table 1
Checklist of potential beneficial services provided by groundwater unit.

Beneficial Service Category	Sub-Category	Applicable?
1) Extractive Use	• Public potable water supply	☐
	• Private/domestic potable water supply	☐
	• Agricultural water supply (incl. irrigation, livestock, aquaculture)	☐
	• Industrial water supply	☐
	• Mining and oil and gas extraction	☐
	• Geothermal energy	☐
2) Non-Extractive Use: *Discharge to Surface Water*	• Water supply via surface water discharge (springs, streams, lakes, etc.)	☐
	• Support of ecological habitat such as wetlands, lakes, streams, etc.	☐
	• Support of recreational activities (fishing, swimming, etc.)	☐
3) Non-Extractive Use: *Stock Value*	• Water storage	☐
	• Prevention of ground surface subsidence	☐
	• Prevention of seawater intrusion	☐
	• Maintenance of hydraulic head regime to protect high-quality units (saline water flow induced by over-pumping)	☐
	• Retention and/or dilution of contaminants that might otherwise discharge to higher quality aquifer or surface water	☐
	• Disposal of waste liquids in saline aquifers	☐
4) Option Value	• Back-up water supply in event of shortage	☐
	• Reserve for future generations	☐

3.2. Remediation objectives to address lost services

Sustainable remediation objectives for impacted groundwater should aim to restore the lost service and protect the users of that service (humans, ecosystems, etc.), while preserving the other services still provided by the groundwater unit and other potentially interconnected units. Chemical contamination does not impair the non-extractive, stock services provided by the groundwater, such as prevention of subsidence, control of seawater intrusion, etc. (see Table 1). However, preservation of these unimpaired services may act as a constraint on the remediation program, for example, by limiting the maximum rate at which water may be pumped from the aquifer without inducing subsidence. Similarly, pumping of groundwater from a contaminated zone within a drinking water aquifer for treatment and disposal at ground surface may consume a volume of fresh water from aquifer storage that exceeds the original volume of the impacted groundwater.

Non-extractive, discharge services may be impaired if the contaminated groundwater discharges to a surface water body that is used as a water supply, a recreational resource, and/or an ecological habitat. The compensable value of a surface water supply can be estimated based on replacement cost. However, estimation of the compensable value for impaired ecological habitats and the supported ecosystems, until such time as recovery is achieved, can entail a relatively complex analysis (43 CFR §11.71(l)), which may be addressed outside the context of the groundwater remedy evaluation. Valuation, compensation, and/or restoration of ecological services are not addressed within the scope of our paper.

3.3. Development of remedial strategies that are commensurate with lost value

To achieve remediation objectives in a sustainable manner, in addition to conventional remedy selection criteria, the remediation technologies under consideration should be evaluated based on the associated investment, in terms of capital and resource consumption, relative to the value of the lost service. For an impacted groundwater unit, the lost value is a function of the prior quality and reliability of the impacted resource, as well as the cost and availability of alternative water sources. As noted earlier, in the context of natural resource damage assessment, the damage caused by groundwater contamination is the sum of the *restoration cost* plus the *compensable value* of the lost service until restoration is achieved. Within the context of remedy selection, the compensable value may be considered the cost of the next more expensive water supply that must be accessed so as to replace the impaired groundwater source. In economic terms, restoration methods whose costs are greater than the compensable value of the lost service will fail to meet sustainability objectives because they consume greater value than they restore.

An automobile damaged in an accident provides a useful analogy. If the auto is damaged to an extent that the repair cost would exceed its value, an insurance company will compensate the owner with a new automobile rather than repair (restore) the damaged one. With regard to groundwater impacts, if the lost extractive service of a drinking water well is compensated by an alternate water supply (e.g., a municipal water connection or a relocated well) or by treatment of the extracted water, then remediation serves to address only the option value of the aquifer, i.e., its future use as a reserve water supply. This is not to say that remediation should not be conducted in accordance with applicable regulatory requirements, or that a “no action” approach is preferred. Rather, under a sustainable approach, the nature of the lost service should be considered to ensure that the timeframe and resource consumption of the remedy is commensurate with the value to be restored.

In the case of a drinking water well that is replaced by an alternate water supply (or by treatment), the groundwater remediation program can logically consist of a lower-intensity, longer-term remedy, such as natural attenuation, as opposed to a higher-intensity, shorter-term remedy, such as enhanced bioremediation, chemical oxidation, or groundwater pumping and treatment. In this case, the resource consumption (energy, capital, etc.) and service loss (loss of water from storage, etc.) of the high-intensity, shorter-term remedy exceeds the option value that is to be restored. If, on the contrary, the lost drinking water well cannot be compensated with an alternate source, then the remediation must address the full extractive value and a higher-intensity, shorter-term remedy may be warranted.

This concept can also be illustrated with regard to brackish aquifers, which, consistent with US regulatory programs, have an option value as a future reserve water supply. In the event of contamination, the present-day compensable value for the loss of the brackish groundwater can be estimated as the cost of replacement by an available fresh water supply (e.g., municipal water system) minus the cost that would be required to render the un-

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impacted brackish water usable as drinking water (UKEA, 2007). In arid regions of the world (e.g., Israel, Western US, etc.), the brackish water may be in use as a drinking water or irrigation water supply, following desalination. In such case, the compensable value for loss of the impacted zone of the aquifer would correspond to the lowest of the costs of replacing the impacted water with an alternative brackish water supply, relocating the water extraction point, augmenting the water treatment process to address the chemical impacts, or a combination thereof.

However, if the brackish groundwater is not presently in use but is considered a future reserve water supply, the option value would be lower yet. In this example, the cost of active pumping and treatment to restore the lost service of the brackish groundwater unit could quickly exceed its compensable value. In such case, remedies such as in-situ treatment or natural attenuation may serve as more sustainable alternatives to restore the lost service and protect potential future users of the brackish groundwater, at costs of capital and resource consumption that are more commensurate with the lost value.

4. Practical steps for application of natural resource valuation concepts in development of a sustainable remediation plan

Based upon a synthesis of US and international guidelines, we have developed the following methodology for incorporation of groundwater valuation and restoration concepts in the remedy selection process:

Step 1: Characterize Properties of Groundwater Body: Define location, dimensions, hydrogeologic features, interconnected aquifers, water quality, yield, and current uses.

Step 2: Define Baseline Beneficial Services: Compare groundwater body to list of potential services (see Table 1) and identify applicable benefits prior to contamination, based on current, planned, or reasonably anticipated uses. “Baseline” refers to the baseline service prior to injury, not to the baseline chemical condition. Extractive uses identified for the groundwater should be current uses or planned, committed uses, rather than speculative.

Step 3: Define Change or Injury: Quantify the change to groundwater quality, sustainable yield, or surface discharge rate caused by the contamination. Relevant impacts to be quantified include the nature, concentration, and extent of groundwater contamination; exceedance of applicable water quality or regulatory criteria; impacts on existing extraction wells; reduction in allowable pumping; and contamination of surface water via discharge; etc.

Step 4: Characterize Loss of Service: For the baseline services identified in Step 2, identify: a) the services that have been lost or impaired and the users of those services and b) the services which remain intact. Note that, if, for example, chemical concentrations exceed drinking water criteria, the groundwater may still meet other less stringent extractive uses, such as irrigation. Non-extractive stock uses will not normally be affected by chemical contamination. Water in storage in the aquifer may be impaired but care should be taken not to double count the impact as both a loss of extractive use and a loss of storage. Impacts on non-extractive discharge uses will depend on whether affected groundwater discharges to a surface water body.

Step 5: Define Remediation Objectives: The primary remediation objectives for an impacted groundwater unit are directed toward protection of public health and the environment, and are commonly specified under applicable environmental regulations. Regulatory criteria often specify maximum allowable concentrations of chemicals of concern in the groundwater, as a function of the quality, yield, and use of the groundwater unit. In regions where regulations do not establish numerical criteria or allow site-specific considerations, risk-based assessment protocols may be applied to develop generic or site-specific criteria that are protective of human health under relevant use scenarios (ASTM, 2010a, 2010b).

For development of a sustainable remediation strategy, these remediation objectives should incorporate natural resource considerations, including:

- Restoring or replacing the lost services of the impacted groundwater unit;
- Providing a replacement resource during the time period of remediation (if needed); and
- Preserving the unimpaired services of the impacted groundwater unit during and after the remediation process (i.e., other extractive and non-extractive services).

Health protection and resource protection objectives are complementary, as protection of the resource protects the users of that resource.

Step 6: Evaluate the Actions Necessary to Compensate Lost Service During the Period that Remediation is Underway: The compensable value of an impaired groundwater resource serves as point of reference for development of a sustainable remediation plan. For extractive services (drinking water, irrigation water, etc.), the compensable value of the lost service is the cost of the next more expensive water supply or the simplest, effective action needed to substitute or treat the groundwater that is now unfit for its prior use. For a contaminated drinking water, the compensable value may correspond to the cost of installing a new well outside of the impacted zone or conducting surface treatment of the contaminated water to meet the relevant use criteria. For non-drinking water units, with no current use and only a potential or hypothetical use under applicable regulatory criteria, the applicable use is an option value, for which the compensable value may be relatively low during the period of remediation, as actual extractive use may not occur. Non-extractive, stock services should not be affected by chemical contamination, but can be affected by the remedial action.

Step 7: Evaluate Alternative Remedies to Develop Sustainable Remediation Strategy: The remedy selection process involves identification and screening of alternative groundwater remediation methods based upon conventional evaluation criteria, supplemented by natural resource considerations. To this end, both active and passive remediation technologies can be evaluated against the remediation objectives defined under Step 6, which incorporate human health, environmental, and resource protection criteria. Each technology or combination of technologies should be evaluated using conventional remedy selection criteria (long-term effectiveness; reduction of the toxicity, mobility, or volume of waste; etc.), in accordance with applicable guidelines (ASTM, 2010a, b; UKEA, 2004; USEPA, 1997) to assess their relative performance in achieving these remediation objectives.

Consideration of resource service and compensable value may serve as a distinguishing factor among remedies that are equally effective for health protection. Each remedy should be compared to the list of applicable groundwater services (e.g., see Table 1), to assess the effects on both the lost service that is to be restored and the intact services that are to be protected. For

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example, for a low quality aquifer that is not presently used for drinking water, both natural attenuation and active remediation may prove protective of the health of future users; however, the cost of the natural attenuation remedy may be more consistent with the lost option value, while an active remedy may consume greater resource value, in terms of energy and, in some cases, fresh water (e.g., for aquifer flushing), than had been lost due to contamination. A sustainable remediation strategy will restore lost services with minimal impact on remaining services, in a manner that is consistent with the compensable value of the lost service.

Table 2 summarizes two examples of this remedy selection process, one for a high-quality aquifer used as a public water supply and the other for a lower quality aquifer not currently used as a drinking water supply. In each case, two remedial options are considered, corresponding to a higher-intensity and a lower-intensity remediation strategy. In these examples, both options achieve health protection criteria in a reasonable time period; however, the lower-intensity option is found to replace lost services and protect intact services in a more sustainable manner.

5. Case study: sustainable remedy evaluation for groundwater impacts at louisiana oil and gas facility

5.1. Case study step 1: characterization of the impacted groundwater body

This case study involves shallow groundwater impacts by saline produced water associated with historic oil and gas exploration and production activities. The regional aquifer at the site, currently being used for irrigation purposes, is an alluvial aquifer encountered at approximately 30 m below ground surface (bgs) and capable of significant yield to a pumping well (>5 m^3 per minute). In addition, under a portion of the site, a silty sand unit is encountered within an overlying surface clay layer.

The environmental site investigation found that produced water spills or leaks had resulted in elevated salinity within the shallow groundwater unit but no impacts on the underlying regional aquifer (see Fig. 1). The shallow sand unit is encountered at approximately 12 m bgs and has an average thickness of

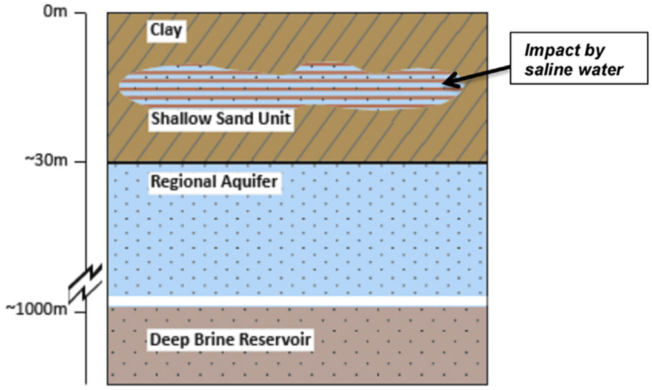

Fig. 1. Case study: Geologic cross-section of study area.

Table 2
Example scenarios of sustainable remedy selection process.

Step	Example 1	Example 2
1) Physical Properties of GW Unit	High water quality, high yield aquifer.	Moderate water quality, moderate to low yield aquifer.
2) Baseline Beneficial Services	• Current public water supply (PWS) • No discharge to surface water; so no non-extractive discharge use. • Non-extractive stock use: water storage, control of subsidence, and control of seawater intrusion.	• No current, planned, and reasonably anticipated near-term use; Option value only. • No discharge to surface water; so no non-extractive discharge use. • Non-extractive stock use: Water storage, control of subsidence.
3) Change or Injury	• PWS well impacted by benzene • Large plume size • Concentrations 20x drinking water criteria	• Aquifer impacted by chlorinated solvents and DNAPL • Moderate plume size • Concentrations >100x drinking water criteria
4) Loss of Service	Public drinking water supply well	Option value as future water reserve
5) Remediation Objectives	• Meet health protection criteria • Restore/replace drinking water service • Minimize effect on unimpaired services	• Meet health protection criteria • Restore option value • Minimize effect on unimpaired services
6) Compensable Value/Action	Restoration of water supply by wellhead treatment or new well outside of plume area.	No specific action required to replace option value in interim.
7) Remedy Evaluation and Selection		
Potential Remedy Options	*Option 1: High-Intensity, Short-Term* • Restore water supply with point of use treatment • P&T plume area • Expected time to meet criteria: 5 years *Option 2: Moderate-Intensity, Moderate-Term* • Restore water supply with point of use treatment • Conduct P&T to remove plume hot spots and stabilize plume, with minimal draw of fresh water from surrounding aquifer • Address plume stabilization/trends using MNA • Expected time to meet drinking water criteria in plume: 15 years	*Option 1: High-Energy, Short-Term* • In-situ thermal treatment of impacted area • Expected time to meet drinking water criteria in plume: 2 years *Option 2: Lower-Energy, Longer-Term* • MNA to demonstrate plume stability, 5–10 years • Expected time to meet drinking water criteria in plume: 50 years
Remedy Evaluation	• Both options meet health protection criteria in reasonable timeframe, given interim replacement of water supply • Option 2 meets health protection criteria and restores drinking water service with less impact on intact services of water storage, subsidence, seawater intrusion, etc., and lower resource consumption.	• Both options meet health protection criteria in reasonable timeframe, given absence of use. • Option 2 meets health protection criteria and restores option value with less impact on intact services of water storage, subsidence, etc., and lower resource consumption.

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approximately 10 m. The background TDS of the sand unit is less than 1000 mg/L and the estimated maximum sustainable yield is approximately 10 L per minute. Local irrigation wells draw water from the underlying regional aquifer, but the shallow sand unit is not currently used as a drinking water or irrigation water supply. However, under applicable state classification criteria, the shallow sand unit is considered an aquifer that could potentially supply drinking water to a domestic water supply.

5.2. Case study step 2: definition of baseline beneficial services of shallow sand unit

The potential beneficial services of the shallow sand unit have been evaluated based on the range of services identified on Table 1 of this paper. There is no current, planned, or reasonably anticipated extractive use of the shallow sand unit, and the unit does not discharge to surface water. Non-extractive stock values include retention or dilution of contaminants that might otherwise penetrate to the depth of the underlying regional aquifer, as well as control of subsidence of the soft clays underling the property. As a potentially usable water source, the shallow sand unit has an option value as a potential future back-up water reserve. Higher quality, easily accessible, alternative water supply sources are located in the near vicinity of the site (i.e., regional aquifer and nearby major river).

5.3. Case study step 3: definition of change or injury to shallow sand unit

A change in groundwater quality within the shallow sand unit was apparently caused by releases of highly saline produced water from former on-site pits. Elevated chlorides and TDS above the Secondary Drinking Water criteria of 250 mg/L and 500 mg/L, respectively, have been observed in samples from groundwater monitoring wells, with chloride concentrations exceeding 40,000 mg/L at some well locations. The plume area exceeding the secondary drinking water criteria is approximately 28 ha, corresponding to an impacted groundwater volume of approximately 750 million cubic meters in the shallow sand unit. The groundwater in the regional aquifer has not been impacted.

5.4. Case study step 4: characterization of loss of service from shallow sand unit

As discussed in Step 2 above, the lost baseline service provided by the shallow sand unit is the lost use of this unit as a back-up water supply and reserve for future generations, which corresponds to a lost option value.

5.5. Case study step 5: definition of remediation objectives for the shallow groundwater unit

The primary remediation objective at this site is protection of human health and the environment. In addition, remediation objectives should include restoration of the lost option value for the shallow sand unit, preservation of unimpaired services (subsidence control), and protection of the underlying regional aquifer.

5.6. Case study step 6: evaluation of actions necessary to compensate lost service during the period of remediation

No specific action is required to replace the option value of the shallow sand unit during the remediation program, due to the presence of sufficient higher quality, easily accessible, alternative water supply sources located in the near vicinity of the site. However, at the same time, the remedial action must not compromise the non-extractive services provided by the shallow sand unit, such as its ability to retain or dilute contaminants that might otherwise discharge to the underlying regional aquifer. In addition, when saturated with groundwater, the shallow sand unit contributes to maintaining saturation of the soft clays underling the property and thereby prevents the subsidence that would be associated with the drainage and compression of these clay layers.

5.7. Case study step 7: evaluation of alternative remedies to develop sustainable remediation strategy

Several remediation options for the shallow sand unit have been evaluated using conventional remedy selection criteria (e.g., long-term effectiveness; reduction of the toxicity, mobility, technical practicability, and volume of waste). Based on the conventional screening criteria, two potential remedial alternatives, both of which meet the remediation objectives for this unit, were selected for further evaluation with regard to resource service and consumption. These two potential remedial options are illustrated on Figs. 2 and 3.

- *Remedy Option 1: Combined Groundwater Flushing and Extraction, with Disposal of Waste Water in On-Site Injection Wells:* This remediation system would include a series of injection and extraction wells, to flush the shallow sand unit with sufficient fresh water to reduce the groundwater TDS to its background concentration (see Fig. 2). Based on design calculations, approximately 1.9 million cubic meters of fresh water would be required, which would be obtained by installing water supply wells within the underlying regional aquifer. To manage the large volume of saline groundwater that would be extracted from the shallow sand unit during the flushing operation, an on-site saltwater injection well would be installed to dispose of the groundwater by means of injection into a deep formation designated for this purpose. This remediation effort would require approximately 5 years for completion.

- *Remedy Option 2: Groundwater Monitoring:* The groundwater monitoring program would entail 5–10 years of monitoring

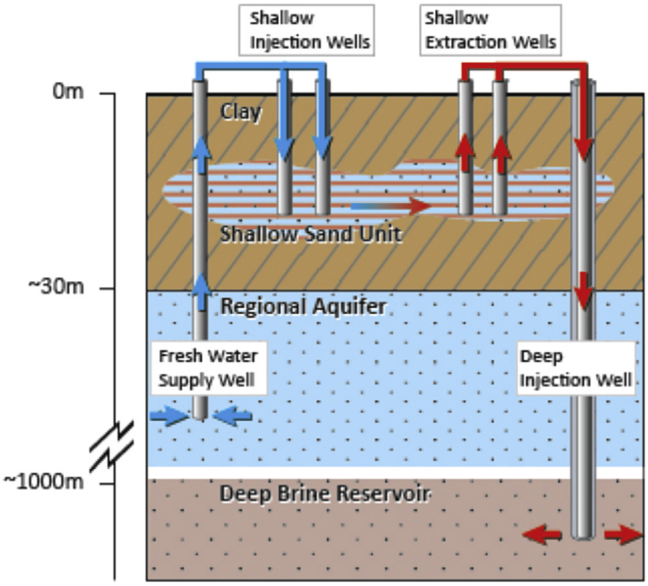

Fig. 2. Case study – remedy option 1: Combined groundwater flushing, extraction, and deepwell disposal.

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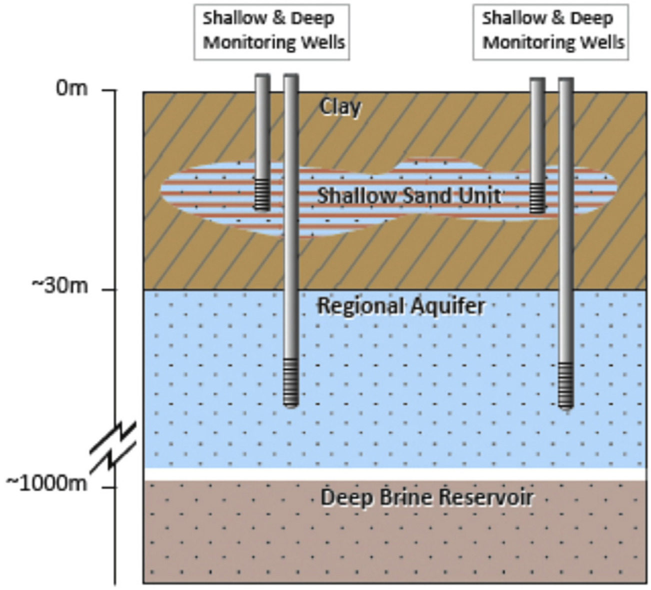

Fig. 3. Case study: Remedy option 2: Groundwater monitoring.

within the shallow sand unit, as well as the underlying regional aquifer (see Fig. 3). This monitoring would be conducted to assess plume stability and to ensure that current conditions are protective of the underlying regional aquifer. Based upon the hydrogeologic information collected to date, saline groundwater is not expected to seep downward into the underlying regional aquifer at a rate sufficient to cause a groundwater quality impact. However, under this remedy option, if monitoring were to detect such an impact, additional remedial measures would be implemented to address the potential resource damage.

Both of these remedial options meet the objectives for protection of human health and the environment. However, consideration of resource service and compensable value clearly distinguishes between the two options. Option 1, while achieving applicable criteria in a timely manner, significantly reduces the volume of usable water in storage in the regional aquifer in order to restore the much lower option value of water in the shallow sand unit. The withdrawal of this large volume of water may also risk subsidence effects. Option 2, a less intensive, long-term remedial action, maintains the storage volume and subsidence control benefits of the regional aquifer, maintains the contaminant retention function of the shallow sand unit, and ultimately restores its option value by natural attenuation. Option 1 requires consumption of energy and a large volume of un-impacted water from the regional aquifer, and generates a large volume of waste. Therefore, based upon available information, Option 2 is the more sustainable remedial alternative for protection of human health and resource value.

6. Conclusions

In this study, we have applied the concepts of natural resource assessment and valuation to the remedy selection process as a tool for developing sustainable groundwater remediation strategies. Our evaluation supports the following conclusions:

1) Remedial alternatives that, based on conventional remedy selection criteria, are expected to provide equal protection to human health may nevertheless entail very different net effects on the services provided by the groundwater resource.
2) Failure to consider natural resource implications poses concern with regard to damage to the groundwater resource undergoing remediation, as well as investment, in terms of capital and resource consumption, that is disproportionate to the value of the impacted groundwater.
3) As a supplement to conventional remedy selection criteria, resource valuation concepts can be used to: i) characterize the baseline services of an impacted groundwater unit, ii) define remediation objectives directed toward replacement of that lost service, protection of its users, and preservation of other unimpaired uses, and iii) select remediation methods that restore the lost service in a manner that is commensurate with its value.
4) Based upon a synthesis of US and international guidelines, a simple step-wise evaluation process can be employed to incorporate groundwater valuation concepts in the remedy selection process.
5) Consideration of resource service and compensable value can serve as a distinguishing factor among remedies that are equally effective for health protection and thereby facilitate development of sustainable remediation strategies.

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