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A decision tree model to estimate the value of information provided by a groundwater quality monitoring network

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Abstract

Nitrate pollution poses a health risk for infants whose freshwater drinking source is groundwater. This risk creates a need to design an effective groundwater monitoring network, acquire information on groundwater conditions, and use acquired information to inform management. These actions require time, money, and effort. This paper presents a method to estimate the value of information (VOI) provided by a groundwater quality monitoring network located in an aquifer whose water poses a spatially heterogeneous and uncertain health risk. A decision tree model describes the structure of the decision alternatives facing the decision maker and the expected outcomes from these alternatives. The alternatives include: (i) ignore the health risk of nitrate contaminated water, (ii) switch to alternative water sources such as bottled water, or (iii) implement a previously designed groundwater quality monitoring network that takes into account uncertainties in aquifer properties, pollution transport processes, and climate (Khader and McKee, 2012). The VOI is estimated as the difference between the expected costs of implementing the monitoring network and the lowest-cost uninformed alternative. We illustrate the method for the Eocene Aquifer, West Bank, Palestine where methemoglobinemia is the main health problem associated with the principal pollutant nitrate. The expected cost of each alternative is estimated as the weighted sum of the costs and probabilities (likelihoods) associated with the uncertain outcomes resulting from the alternative. Uncertain outcomes include actual nitrate concentrations in the aquifer, concentrations reported by the monitoring system, whether people abide by manager recommendations to use/not-use aquifer water, and whether people get sick from drinking contaminated water. Outcome costs include healthcare for methemoglobinemia, purchase of bottled water, and installation and maintenance of the groundwater monitoring system. At current methemoglobinemia and bottled water costs of 150 $/person and 0.6 $/baby/day, the decision tree results show that the expected cost of establishing the proposed groundwater quality monitoring network exceeds the expected costs of the uninformed alternatives and there is not value to the information the

monitoring system provides. However, the monitoring system will be preferred to ignoring the health risk or using alternative sources if the methemoglobinemia cost rises to 300 $/person or the bottled water cost increases to 2.3 $/baby/day. Similarly, the monitoring system has value if the system can more accurately report actual aquifer concentrations and the public more fully abides by managers' recommendations to use/not use the aquifer. The system also has value if it will serve a larger population or if its installation costs can be reduced, for example using a smaller number of monitoring wells. The VOI analysis shows how monitoring system design, accuracy, installation and operating costs, public awareness of health risks, costs of alternatives, and demographics together affect the value of implementing a system to monitor groundwater quality.

1 Introduction

In many places throughout the world, groundwater is the sole drinking water source but is jeopardized by nitrate (NO_3^-)and other pollution from human activities such as agriculture, industry, municipal waste, septic tanks, cesspits, and dairy lagoons (Almasri and Kaluarachchi, 2005). When ingested, nitrate decreases the ability of human blood to carry oxygen, can result in oxygen deficiency, and cause methemoglobinemia (blue baby syndrome) and other health problems including dizziness, headache, loss of muscular strength, hemolysis, seizures, or, in the most extreme cases, death (Majumdar, 2003). Infants are more susceptible than adults (Lorna, 2004), with susceptibility depending on the NO_3^- concentration in polluted water (Walton, 1951). For example, infants who drink water with NO_3^- concentrations less than 45 mg L^{-1} are unlikely to get the disease while 57 % of infants who drink water with NO_3^- concentrations between 45 and 225 mg L^{-1} will experience methemoglobinemia; almost all infants who drink water with NO_3^- concentrations greater than 225 mg L^{-1} will be affected. These health risks

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create a need to intensively monitor and manage groundwater resources that might be susceptible to nitrate contamination.

Effective groundwater monitoring and management must provide reliable information about groundwater quality, likelihood of different groundwater quality outcomes, and the costs and consequences of potential outcomes and actions. However, information is not free; it requires money and time to acquire (Sakalaki and Kazi, 2006). Thus when deciding whether to ignore a pollution problem, use alternative sources of water, or design and implement a groundwater quality monitoring network, it is important to consider the value of information (VOI) provided by the monitoring network. The VOI compares the present-value, expected net benefits of collecting additional information to reduce or eliminate uncertainty associated with the outcomes of a decision to the present-value, expected net benefits of a preferred uninformed alternative (Chia-Yu Lin et al., 1999; Dakins, 1999; Dakins et al., 1994, 1996; Delquié, 2008; Rajagopal, 1986; Repo 1989; Sakalaki and Kazi, 2006; Yokota and Thompson, 2004a,b). VOI makes explicit any expected losses from errors in decision-making due to uncertainty and identifies the preferred information collection strategy as one that leads to the greatest expected net benefit to the decision-maker (Yokota and Thompson, 2004a).

To estimate net benefits, managers and decision makers can use expected utility (EU) theory (Delquié, 2008). In economics, utility is a set of numerical values that reflect consumer satisfaction from receiving a good or service such as clean drinking water. EU is calculated by weighting the utility of each potential outcome (such as polluted or clean drinking water) by the outcome probability (Perloff, 2008). For public policy decisions where consequences are small compared to the scale of the overall enterprise, we can substitute expected value (EV; measured in value units such as dollars) for EU (Arrow and Lind, 1970). Like EU, the EV of each decision is calculated by weighting the value of each potential outcome by the outcome probability.

A decision tree model describes the logical structure of the decisions, uncertainties, and potential outcomes (Fig. 1), and can help estimate EU or EV (Lund, 2008). In the figure, boxes denote choice nodes where decisions are made. Circles denote chance

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nodes where information is revealed. Each branch emanating from a choice node represents an alternative and each branch emanating from a chance node represents an uncertain outcome with a specified probability. Each outcome consequence is shown on a terminal branch at the far right of the tree. In Fig. 1, the decision maker has two uninformed alternatives (branches 1 or 2) or may acquire more information about the system to later make a more informed decision (branch 3).

The VOI is measured ex-ante as the difference between the EUs or EVs of the informed and uninformed branches (Delquié, 2008; LaValle, 1968). When the EV of the informed alternative is larger than the EV of the uninformed alternative, VOI is positive and there will be benefit to acquire more information.

Willingness to pay (WTP) is another widely used method to estimate VOI (Alberini et al., 2006; DeShazo and Cameron, 2005; Dickie and Gerking, 2002; Engle-Warnick et al., 2009; Latvala and Jukka, 2004; Molin and Timmermans, 2006; Roe and Antonovitz, 1985; Sakalaki and Kazi, 2006) and is defined as the maximum amount a person or a DM is willing to pay to receive a good or to avoid something undesirable (Perloff, 2008). Researchers survey individuals and ask them to state how much they are willing to pay for additional information (Alberini et al., 2006; Atkins et al., 2007; Pattanayak et al., 2003). Alternatively, researchers can embed the WTP questions in valuation experiments where participants express their WTP for certain outcomes and then receive rewards/penalties based on their responses and subsequent chance outcomes (Friedman and Sunder, 1994). Both WTP methods require a large number of participants, repeat the method multiple times with individual participants, measure WTP ex-poste from the responses, and assume participants understand the meanings, outcomes, and likelihoods of the situation posed and are vested in the outcome. For situations like a groundwater monitoring system design where there are only a small number of decision makers, the EU method can estimate how rational people should value information and provides an upper bound for WTP sufficient for VOI analysis.

This paper uses a decision tree model to estimate the value of information provided by a proposed nitrate groundwater quality monitoring network for the Eocene Aquifer, West Bank, Palestine. The proposed monitoring network and placement of observation wells consider uncertainties in aquifer properties, pollution transport processes, and climate (Khader and McKee, 2012). At present, Eocene aquifer managers must decide whether to: (i) ignore the nitrate contamination problem (and face the risk of methemoglobinemia); (ii) recommend households switch to alternative water sources such as bottled water; or (iii) implement the proposed groundwater quality monitoring system then use monitoring results to recommend whether households should either continue to use the aquifer or switch to alternative water sources. These options differ in their implementation costs, outcomes, likelihood that babies will get sick with methemoglobinemia, and associated consequences. These costs, outcomes, and likelihoods are further affected by whether the public will abide with managers' recommendations to use or not use water from the aquifer for in-home consumption. These costs and uncertainties challenge the decision maker and identify the need for a decision tool that can identify the expected values of the options, the value of information provided by the monitoring system, and help decision makers choose a preferred alternative.

Past VOI research in fields like general environmental health, water contamination, and toxicology applications has focused on demonstrating the usefulness of the VOI approach (Yokota and Thompson, 2004b). Here, our three-fold contribution is to (1) use the decision tree framework to estimate the value of implementing a groundwater quality monitoring network, (2) apply the approach to help inform aquifer monitoring and management decisions, and (3) show how the VOI is influenced by a multitude of design, public awareness, financial, demographic, and demographic-hydrogeological factors such as the monitoring system design and accuracy, public abidance with manager recommendations, costs of alternatives, size of the population, and location of the population in relation to areas that pose a health risk.

The next section briefly describes the study area and proposed monitoring network. Sections 3 and 4 present the decision tree components and results from the VOI calculations and sensitivity analyses. Section 5 concludes.

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2 Study area and proposed monitoring network

The methodology of this research is demonstrated using the Eocene Aquifer, which is an unconfined aquifer located in the northern part of the West Bank, Palestine (Fig. 2). Nitrate is the main pollutant in the Eocene Aquifer. The main reasons for nitrate pollution in the aquifer are the excessive use of nitrogen-rich fertilizers and the lack of sewer networks (Najem, 2008). Nitrate pollution may cause methemoglobinemia for people living in the area.

The Eocene Aquifer is used to meet domestic and agricultural demands for more than 207 000 Palestinians living in 66 communities, including 53 000 people in the City of Jenin (PCBS, 2009). Annual population growth in the area is 3.0 % and the average household size is 5.5 (PCBS, 2008).

In prior work, Khader and McKee (2012) used a groundwater flow model, nitrate fate and transport model, and 10 000 Monte Carlo (MC) simulations to capture the effects of uncertainties in aquifer recharge, hydraulic conductivity, and nitrate reaction processes on nitrate concentrations throughout the Eocene Aquifer. The results were estimates of the spatial distribution of nitrate concentrations across 519 active 1000 m by 1000 m aquifer model cells (Fig. 2, right); within each cell there is also a probability distribution of nitrate concentration.

Khader and McKee (2012) also used uncertainties revealed through the Monte Carlo simulations to design a groundwater nitrate monitoring network for the Eocene Aquifer. The design shows the proposed locations of 49 monitoring wells and takes into account uncertainties in climate, aquifer properties, and expected nitrate concentrations. To design the network, Khader and McKee (2012) used a relevance vector machine (RVM) to build a best-fit model of nitrate concentration distribution everywhere in the aquifer for each Monte Carlo subset. The RVM model outputs include the spatial distribution of nitrate concentration everywhere in the aquifer, the uncertainty in the characterization of those concentrations, and the number and locations of "relevance vectors" (RVs). The RVs form the basis of the optimal characterization of nitrate throughout the aquifer and

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can be used to determine the optimal locations of monitoring wells, predict nitrate concentrations throughout the aquifer, and characterize the uncertainties associated with those predictions. Here, we use all these outputs to calculate the value of information associated with the monitoring network.

3 Decision tree analysis

The decision tree depicts the structure of the problem of how to respond to uncertain outcomes like potential aquifer contamination. We consider three alternatives: (i) do nothing (ignore the nitrate pollution problem), (ii) switch to alternative sources of water, or (iii) implement a groundwater quality monitoring network that reduces uncertainty about groundwater quality and informs subsequent manager recommendations such as to continue to use the aquifer or switch to alternative sources (Fig. 3). The decision tree can also be used to calculate the value of information associated with the alternative to monitor to reduce uncertainty.

Ignoring the problem and not testing for nitrate pollution is one uninformed option and means the decision maker will encourage people to use the aquifer and face a health risk if aquifer water is contaminated (nitrate concentration greater than 45 $mg\,L^{-1}$). If the water in an aquifer model cell is contaminated and people who use that water get sick, there will be a cost associated with methemoglobinemia treatment in the form of Methylene blue. Methylene blue converts MHb to hemoglobin, gives immediate relief, but costs about 150 $ per case in the West Bank (http://www.revolutionhealth.com/drugs-treatments/methylene-blue), which is considered a high cost by the people living there (Majumdar, 2003). As a second uninformed alternative, the decision maker can immediately recommend that people not use water from the aquifer and instead switch to alternative sources, such as bottled water. In this case, the supply costs are higher; however, everyone will stay healthy. As a third option, the decision maker can acquire more information about the groundwater quality and the spatial distribution of nitrate concentration. There will be capital costs to design the monitoring network, drill, and

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finish monitoring wells, and on-going costs to regularly collect and analyze groundwater samples and operate and maintain the wells. The decision maker can use monitoring results to estimate groundwater quality throughout the aquifer and then, based on the monitoring results, recommend whether people should (i) continue to use the aquifer, or (ii) switch to alternative sources. However, monitoring and estimation of nitrate concentrations are imperfect, so when people continue to use the aquifer there is still a possibility that the estimated nitrate concentration in their water will differ from the actual concentration. For example, if the monitored/estimated concentration is less than 45 mg L^{-1}, the actual concentration may be larger than 45 mg L^{-1}. In this situation, people still face a health risk, could get sick, and will require methemoglobinemia treatment (even though they followed the decision maker's recommendation to continue to use water from the aquifer). Thus, with monitoring, there are also additional recourse costs that depend on the monitoring results and whether managers subsequently advise households to continue to use the aquifer or use alternative sources. Figure 3 shows this decision tree structure for the case when people fully abide with decision makers' recommendations.

The decision tree structure changes for a second case where only some people abide with decision makers' recommendations (Fig. 4). In this case, there are additional branches from each node where a decision maker recommends what people should do; these branches represent people who (i) abide with, and (ii) ignore decision maker recommendations. Probabilities $A1$, $A2$, $A3$, $A4$, $1-A1$, $1-A2$, $1-A3$, and $1-A4$ define the likelihoods that people will abide with and ignore the recommendations and are not found in Fig. 3 (for the case of full abidance). The additional outcomes represent public awareness and acceptance of decision maker recommendations and ultimately affect the value of information provided by the monitoring system.

Since outcome costs listed in the decision tree occur both immediately and in future years, we use a common 30-yr time horizon (equivalent to the life of the monitoring system) and an interest rate of 5 % to bring all future costs to their present value. We also assume that aquifer nitrate concentrations are temporally static over the 30-yr

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analysis period and people face the same health risk each year. Below we present our methods to estimate the various outcome costs and outcome probabilities listed in the decision tree. Then, we describe how we use the outcome costs and probabilities to compute an expected cost for each alternative and the value of information for the groundwater quality monitoring system.

3.1 Outcome costs

As shown in the decision tree (Fig. 3), there are costs associated with the outcomes resulting from each alternative. These outcome costs include:

1. *Methemoglobinemia treatment*. When aquifer water is contaminated with nitrate and an individual contracts methemoglobinemia, the most common treatment is methylene blue (Majumdar, 2003). The estimated cost of methylene blue treatment for an infant is 150 $ (http://www.revolutionhealth.com/drugs-treatments/methylene-blue). Additionally, we assume that both parents work, so when an infant gets sick at least one parent will stay home for 6 work days to care for the infant, as is common in the West Bank. West Bank wages are typically 50 $ day^{-1}. Thus, there is an additional cost of 300 $ in lost salary associated with the outcome of getting sick.

   To estimate community-wide costs, we scale the individual costs per family by the number of households served by the pumping well and the 30 % fraction of households that use formula rather than breast milk (Ammar et al., 2008). Absent detailed data on the water distribution system in the study area, we assume that the number of households served by a pumping well is proportional to the pumping rate from the well (Khader, 2012). Additionally, the population in the study area is growing by 3 % per year, so the number of people affected and costs in future years also increase.

2. *Switch to alternative sources*. In this option people use alternate water sources to make infant formula rather than polluted groundwater. One alternative water

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source is bottled water which costs about 0.6 \$/infant/day or 220 \$/infant/year. Other alternatives includes home distillation, reverse osmosis (RO), or ion exchange units (Jennings and Sneed, 1996). These units are much more expensive than bottled water and our analysis assumes households will choose the cheaper bottled water option. We use the same methods as for Methemoglobinemia treatment to scale the household cost for bottled water to a community cost.

3. *Monitoring system*. The costs to install and operate the 49 wells comprising the monitoring system include three components (CDLE, 2001):

   – Drilling cost (53.89 $\$\,m^{-1}$ for a well < 15 m deep or 60.45 $\$\,m^{-1}$ for a well > 15 m deep)

   – Finishing cost (49.72 $\$\,m^{-1}$), and

   – Nitrate sampling cost (12 $\$\,well^{-1}\,year^{-1}$). The depth to ground water at each well is estimated using the groundwater flow model developed in Khader and McKee (2012). The total present value cost to install and operate the monitoring system is 0.6 million US\$ and include drilling, finishing, and sampling costs.

   There are also additional costs associated with further decisions and outcomes taken in response to the monitoring results. For example, if monitoring and modeling suggest the aquifer water supplying a pump will not be contaminated (nitrate concentration < 45 $mg\,L^{-1}$), decision makers will recommend people to continue to use that water. But the monitoring system is imperfect and there are still possibilities the actual nitrate concentration will be above 45 $mg\,L^{-1}$ and some people will get sick. In this progression of events, these people will require Methemoglobinemia treatment at costs described in cost item #1 above. Similarly, if monitoring suggests the water in an aquifer model cell supplying a pump is contaminated (nitrate concentration > 45 $mg\,L^{-1}$), decision makers will recommend people who use that water to switch to an alternative source. In this case these people will incur the costs described in cost item #2 above. Together, the expected cost of the monitoring system includes the present value costs of installing and operating the system plus the present value expected costs of recourse actions and outcomes that occur in response to the monitoring results.

3.2 Probability estimation

Probabilities quantify the likelihood of uncertain outcomes such as groundwater quality and public response to decision maker recommendations. We use probabilities to weight outcome costs and determine the expected cost for the set of outcomes associated with an alternative. Below we describe the methods used to estimate the probabilities associated with uncertain groundwater quality and public responses.

3.2.1 Groundwater quality

Here, we use prior Monte Carlo simulation and RVM model results derived from uncertainties in climate, aquifer properties, and expected nitrate concentrations (Khader and McKee, 2012) to estimate the outcome probabilities listed in the decision tree (Figs. 3, 4). We define each probability and present the method to estimate it.

- [$P1$] is the probability that the actual nitrate concentration in an aquifer model cell is less than 45 mg L^{-1}. We estimate this probability by dividing the number of MC simulations where concentration in the aquifer model cell was less than 45 mg L^{-1} by the total number of MC simulations.
- [$P2$] is the probability that the actual nitrate concentration in an aquifer model cell is in the range 45–225 mg L^{-1}. We also estimate this probability from the MC simulations.
- [$P3$] is the probability that the actual nitrate concentration in an aquifer model cell is greater than 225 mg L^{-1}. MC results show that nitrate concentration did not

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exceed 225 $mg L^{-1}$ in any aquifer model cell in any MC simulations. Thus, P3 is zero and we do not consider this outcome in the decision tree.

- $[S/P1]$ is the probability an infant will get sick with methemoglobinemia given the nitrate concentration in an aquifer model cell is less than 45 $mg L^{-1}$. This probability is zero (Walton, 1951).
- $[S/P2]$ is the probability an infant will get sick with methemoglobinemia given the nitrate concentration is in the range 45–225 $mg L^{-1}$. This probability is 57 % (Walton, 1951).
- $[p1]$ is the probability that the monitoring network will suggest nitrate concentration in an aquifer model cell is less than 45 $mg L^{-1}$. We estimate this probability from the RVM model by dividing the number of RVM runs where concentration in the aquifer model cell was less than 45 $mg L^{-1}$ by the total number of runs.
- $[p2]$ is the probability that the monitoring network will suggest nitrate concentration in an aquifer model cell will be in the range 45–225 $mg L^{-1}$. This probability is also estimated from the RVM model like for $[p1]$.
- $[P1/p1]$ is a posterior probability and is the probability that the actual nitrate concentration in an aquifer model cell will be less than 45 $mg L^{-1}$ when the monitoring network suggests the aquifer concentration is less than 45 $mg L^{-1}$. In this circumstance, the monitoring system predicts the correct outcome and we can use Bayes Theorem to calculate this posterior probability from the prior probability $[p1/P1]$ and probabilities $[P1]$ and $[p1]$ that we already know:

$$[P1/p1] = \frac{[P1[p1/P1]}{[p1]} \quad (1)$$

Here, the prior probability $[p1/P1]$ is estimated by jointly considering the MC simulation and RVM results together, and estimating the probability that the monitoring network will suggest nitrate concentration in an aquifer model cell is less

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than 45 mg L^{-1} (RVM results) when the actual nitrate concentration is less than 45 mg L^{-1} (MC simulations). In this case [$p1/P1$] is estimated by dividing the (i) number of runs where concentrations in the RVM and MC simulations are both less than 45 mg L^{-1} by (ii) the total number of runs.

- [$P2/p1$] is the probability that the actual concentration in an aquifer model cell will be in the range 45–225 mg L^{-1} when the monitoring network suggests the concentration is less than 45 mg L^{-1}. This case represents a Type II error – when the monitoring system suggests the aquifer water is safe when in fact the water actually poses a risk. Together, the probabilities for the correct outcome ([$P1/p1$]) and Type II error ([$P2/p1$]) sum to 1 and comprise all possible outcomes for the situation when the monitoring system suggests nitrate concentration in an aquifer model cell will be less than 45 mg L^{-1}. Thus, we use the law of probabilities to estimate [$P2/p1$] as:

$$[P2/p1] = 1 - [P1/p1] \quad (2)$$

- We use similar methods to estimate [$P2/p2$] and [$P1/p2$] as the probabilities that the actual nitrate concentration in an aquifer model cell will be in the ranges of, respectively, 45–225 or 0–45 mg L^{-1} when the monitoring network suggests the concentration will be in the range 45–225 mg L^{-1}. The probability [$P2/p2$] also represents a true outcome while [$P1/p2$] represents a Type I error – monitoring system suggests the water poses a risk when the water is actually safe.

The above probability estimates are for an individual aquifer model cell. Since the aquifer is heterogeneous, the probability values may also differ by aquifer model cell. In the analysis of alternatives, we use probabilities associated with aquifer model cells that have a withdrawal well and supply people water.

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3.2.2 Public response

As shown in Fig. 4, whether people abide by or ignore decision maker recommendations is an important factor that determines the structure of the decision tree and likelihood of outcomes. To estimate the likelihood that people will abide by decision maker recommendations, we invited two hundred fifty people living in the area of the Eocene Aquifer to participate in a survey that asked them their perceptions of the current situation of water quality and quantity and how they would respond in four hypothetical scenarios where decision makers recommend they use/not use aquifer water. One hundred and ninety-six people living in 26 communities responded. Kader (2012) provides a full description of the survey method and results; here, we focus on the portion of the survey that probes how participants may respond to manager recommendations to use or not use water from the Eocene Aquifer. In the first two hypothetical scenarios, the government simply declared the groundwater is either (i) safe or (ii) not safe to drink. In the third and fourth scenarios, the government monitored and tested the aquifer water then declared the water either (iii) safe or (iv) not safe (Khader, 2012).

Statistical analysis of the responses to the four questions associated with these four scenarios provides estimates of the abidance probabilities $A1$–$A4$ (Table 1). Absent monitoring, less than 30 % of participants would abide with recommendations to use the aquifer. However, 96 % of participants would abide with a decision maker's recommendation if the recommendation is to not use the aquifer. With monitoring in place, more people will abide with the recommendations to use or not to use the aquifer (62 % and 97 %). Across all the scenarios, people are more likely to abide with a decision maker's recommendation when the recommendation is to not use the aquifer. Together, the survey responses suggest which types of messages people will follow and characterize the probabilities people will abide with decision maker recommendations.

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3.3 Expected costs of alternatives and value of information

We convert all outcome costs to their present values then calculate the expected cost of an alternative as a weighted average of all outcome costs associated with the alternative. We use the outcome probabilities ($p1$, $p2$, $P1$, $P2$, $A1$, $A2$, $A3$, and $A4$ in Figs. 3, 4) as the weights. In the Eocene Aquifer study, present-value, expected costs incurred by decision makers and the public serve as an adequate proxy for expected value since these costs are the principal factors affecting the expected value of each alternative. A probability-weighted, expected-cost metric is risk-neutral and appropriate for the case when the magnitudes of outcome costs are small, there are similar types of outcomes across the alternatives, and the decision maker does not have strong preferences among outcomes with large and small magnitudes.

We then use the present-value expected costs to estimate the value of information of the monitoring network. This value is the difference between the expected costs of implementing the monitoring network and the lowest-cost, uninformed alternative.

4 Results and discussion

The present value expected costs of the do-nothing option (continue to use the aquifer), switch to alternative sources, and install and use the monitoring system options range between 6 and 7 million $ (Fig. 5). The two uninformed options of do-nothing and switch to alternative sources have nearly equivalent expected costs; the expected cost to switch to alternative sources is slightly smaller and identifies use alternative sources as the preferred response to potential nitrate pollution in the Eocene Aquifer. The expected cost for the monitoring system is larger than either of the uninformed options and suggests that information provided by the monitoring system does not have value under the modeled assumptions. The monitoring system does not have value because implementing an uninformed option gives a lower expected cost.

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When we relax the assumption about full abidance and consider that some people will ignore decision makers' recommendations, the expected cost of the monitoring system slightly increases (purple bars in Fig. 5). This result shows how public awareness, acceptance, and compliance with health safety messages affect the value of information provided by a monitoring network. The result suggests that public outreach to local communities through town hall meetings, media advertising, education campaigns in schools, and the like should be part of monitoring programs since more people abiding with decision maker recommendations reduces overall costs and increases the value of information provided by monitoring.

Setting aside the 0.6 million $ present value cost to install and operate the proposed monitoring system over its 30-yr life from the VOI calculation (i.e. consider only the expected costs associated with recourse actions taken in response to monitoring results) shows the upper bound on willingness to pay (WTP) for a monitoring system (Fig. 6). This WTP is measured ex-ante, is below the expected costs to install and operate the system, and reiterates, as with expected costs, that the monitoring system does not have value.

However, this ex-anti approach to estimate WTP allows us to further study monitoring systems with unknown installation and operation costs such as a hypothetically perfect monitoring system that always estimates nitrate concentrations in their actual ranges. In the decision tree model, we represent a perfect monitoring system by changing the values of the posterior probabilities [$P1/p1$] and [$P2/p2$] to 1 and the probabilities associated with type I and II errors ([$P2/p1$] and [$P1/p2$]) to 0. Model results for the perfect monitoring system show WTP increases (Fig. 6). Should people fully abide with decision maker's recommendations, WTP for perfect monitoring exceeds the present value costs to install and operate the proposed (imperfect) monitoring system. For the case of partial abidance with decision maker recommendations, WTP for perfect monitoring is below the costs of the proposed system. When WTP for a perfect system is below the actual system cost, analysts often suggest that decision makers should not invest in monitoring (Yokota and Thompson, 2004b). However, lowering the monitoring

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system capital and operating costs (red line in Fig. 6) to \$0.2 million (in the case of full abidance) or \$0.1 million (with partial abidance) would make the monitoring system investment worthwhile. Decision makers could lower the monitoring system capital costs by reducing the number of monitoring wells or moving wells to locations where it is less expensive to install them. Alternatively, decision makers could improve monitoring system accuracy by including other sources of uncertainty like human activities and on-ground nitrate loading (Khader and McKee, 2012). Together, the WTP results show how monitoring system size, design, accuracy, public abidance with decision maker recommendations, and capital and operating costs together influence the value of information provided by the monitoring system.

Sensitivity analysis further shows how the value of information provided by the monitoring system is affected by financial, demographic, and demographic-hydrogeological factors. For example, when the cost of methylene blue treatment rises above 300 \$/person, the expected cost for the do-nothing option surpasses the expected costs for the monitoring system and monitoring is preferable to doing nothing (results not show). Similarly, the monitoring system is preferable to the bottled water option when the bottled water cost rises to 2.3 \$/baby/day. When the population using the aquifer increases to 1.2 million, the expected costs for both uninformed options surpass the expected cost for the monitoring system and the monitoring system has value. These results show that financial characteristics of the uninformed alternatives as well as demographics affect the value of information.

Beyond the demographic factor of the number of people using the aquifer, monitoring system VOI is also influenced by where people are located relative to aquifer hydrogeological characteristics such as nitrate-contaminated areas. To study this effect, we first noted that in the prior results, 86 % of the population is served by wells that draw from locations in the aquifer where the expected nitrate concentration is greater than 45 $mg\,L^{-1}$ and may pose a health risk. (Similarly, 14 % of the population is served by wells that pose little health risk.) These results stem from the prior assumption that the number of households served by a pumping well is proportional to the well pumping

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rate. Second, we varied from 0 to 100 % the percent of the population served by wells that pose a health risk and calculated the expected costs for each alternative with partial abidance. These scenarios can be interpreted to represent either demographic (i) proximity to wells where nitrate concentration is greater than 45 $mg L^{-1}$, or (ii) migration towards or away from such wells. As anticipated, results show do-nothing is the low-cost, clearly-preferred option when 0 % of the population is at risk (Fig. 7, far right). Similarly, switch to alternative sources is the low-cost, preferred option when 100 % of the population is served by wells where nitrate poses a health risk (Fig. 7, far left). Interestingly, expected costs increase for all options as more of the population is served by wells that pose a risk. However, expected costs increase fastest for the do-nothing option and slowest for the alternative sources option so that alternative sources become preferable when 86 % or more of the population is served by wells that pose a health risk. Across the scenarios, the expected costs for the monitoring system are always greater than costs for one of the uninformed options. However, the gap narrows between the expected costs of the monitoring system and the least-cost uninformed option as more of the population is served by wells that pose a health risk. This gap represents the value of information of the monitoring system, is less than the 0.6 million $ capital and operating cost of the monitoring system in scenarios where more than 86 % of the population is served by wells that pose a health risk, and suggests, as discussed previously, that there is value to a monitoring system with lower capital and operating costs. This value is also affirmed by noting that the decision maker does not presently know what percentage of the population faces a health risk. Thus, should s/he recommend do-nothing or switch to alternative sources? To answer this question, the decision maker will need to monitor and the $0.3 million gap between the expected costs of do-nothing and switch to alternative sources when 100 % of the population is at risk represents an upper bound on decision maker's WTP to monitor. The decision maker's actual WTP may be less and will depend on his/her prior information regarding aquifer contamination and the likelihood they associate with the outcome that the entire population will be at risk. These scenarios show that monitoring system VOI is also influenced by where people are located relative to aquifer hydrogeological characteristics such as nitrate-contaminated areas.

Together, the decision tree model, VOI results, and sensitivity analyses show that the proposed monitoring system for the Eocene Aquifer does not have value and that uninformed options like switch to alternative sources are lower-cost. However, the VOI provided by the monitoring system is affected by important public acceptance, system design, financial, demographic, and demographic-hydrogeological factors such as whether people abide with decision maker recommendations, monitoring system accuracy, installation and operation costs, costs of uninformed alternatives, the number of people served by the aquifer, and where people live in relation to areas with nitrate concentrations that pose health risks. These results indicate that there is WTP for a monitoring system but the system installation and operating costs for the proposed system will need to decrease by half to 0.3 million $ or less for the system to have value. Besides using fewer monitoring wells (with potentially some loss in concentration prediction ability), decision makers could alternatively lower the monitoring system cost by including costs to drill and finish wells as additional criteria in the RVM design and selection of monitoring well locations. This latter approach identifies the potential benefit to embed value of information methods directly in the monitoring network design process.

5 Conclusions

This paper presents a method to estimate the value of information provided by a groundwater quality monitoring network located in an aquifer whose water poses a spatially heterogeneous and uncertain health risk. We used a decision tree to describe the structure of the decision alternatives facing the decision maker, likelihoods, and expected outcomes from these alternatives. The alternatives include: (i) do nothing (continue to use the aquifer ignore the health risk of nitrate contaminated water), (ii) switch to alternative water sources, or (iii) implement a previously designed groundwater quality monitoring network that takes into account uncertainties in aquifer properties, pollution transport processes, and climate. We estimate the value of information provided by the monitoring network as the difference between the present-value, expected costs of the monitoring network and the lowest-cost uninformed alternative.

We illustrated the method for the Eocene Aquifer, West Bank, Palestine where methemoglobinemia is the main health risk associated with nitrate pollution. We estimated the expected costs of each alternative as the weighted sum of the costs and probabilities (likelihoods) associated with the potential outcomes resulting from the alternative. Potential outcomes included contaminant concentrations in individual aquifer model cells, concentrations reported by the monitoring system, whether people abide by manager recommendations to use/not-use aquifer water, and whether people get sick from drinking contaminated water. The likelihoods of these outcomes were derived from Monte Carlo simulations of uncertain aquifer properties, RVM results, surveys of people's likely responses to official pronouncements regarding aquifer water quality, and prior heath studies. Outcome costs included healthcare for methemoglobinemia, purchasing bottled water, and installing and maintaining the groundwater monitoring system.

Decision tree results show that the expected cost of establishing the proposed monitoring network exceeds the expected costs of the uninformed alternatives and there is not value to the information the system provides. Eocene Aquifer managers should instead recommend that families use alternative sources like bottled water to make baby formula.

The value of information provided by the monitoring system is further diminished when only part of the affected population abides with decision maker recommendations to user/not use the aquifer. However, should bottled water costs increase to 2.3 $/baby/day, methemoglobinemia cost rise to 300 $/person, or the population served by aquifer increase above 1.2 million persons, decision makers should prefer the monitoring system to switching to alternative sources or ignoring the health risk.

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A monitoring system with lower installation and operating costs or that more accurately reports actual aquifer concentrations would likewise have value. Designers could lower system costs by either (i) using fewer monitoring wells, or (ii) including the costs to drill and finish wells as additional criteria in the RVM to select monitoring well locations.

The VOI analysis offers Eocene Aquifer managers specific recommendations to respond to the nitrate contamination in the West Bank, Palestine. The analysis also shows how the value of information provided by a monitoring system is affected by important system design, public acceptance, financial, demographic, and demographic-hydrogeological factors like monitoring system accuracy, installation and operation costs, whether people abide with decision maker recommendations, costs of uninformed alternatives, the number of people served by the aquifer, and where people live in relation to areas with nitrate concentrations that pose health risks. There is value to monitor groundwater quality in the Eocene Aquifer but not using the proposed monitoring system.

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Table 1. Probabilities participants will abide with decision maker recommendations.

Recommendation		Label	Probability of abidance Mean value	Standard deviation	95 % C.I
Without monitoring	Use the aquifer	[*A*1]	0.294	0.457	0.230–0.358
	Use other sources	[*A*2]	0.959	0.199	0.931–0.987
With monitoring	Use the aquifer	[*A*3]	0.624	0.486	0.556–0.692
	Use other sources	[*A*4]	0.969	0.174	0.945–0.993

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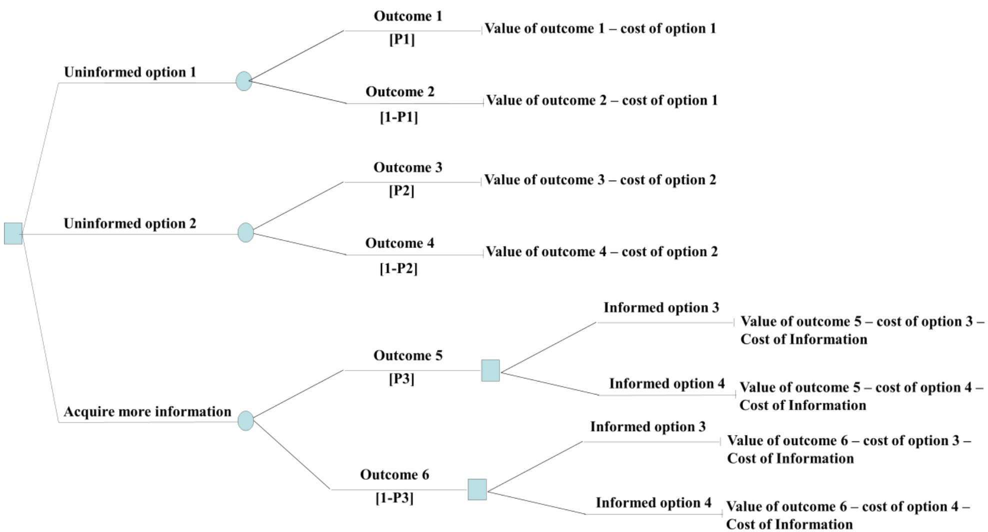

Fig. 1. Example decision tree with three alternatives yielding six potential outcomes with probabilities $P1$, $P2$, $P3$, and complements $1-P1$, $1-P2$, and $1-P3$.

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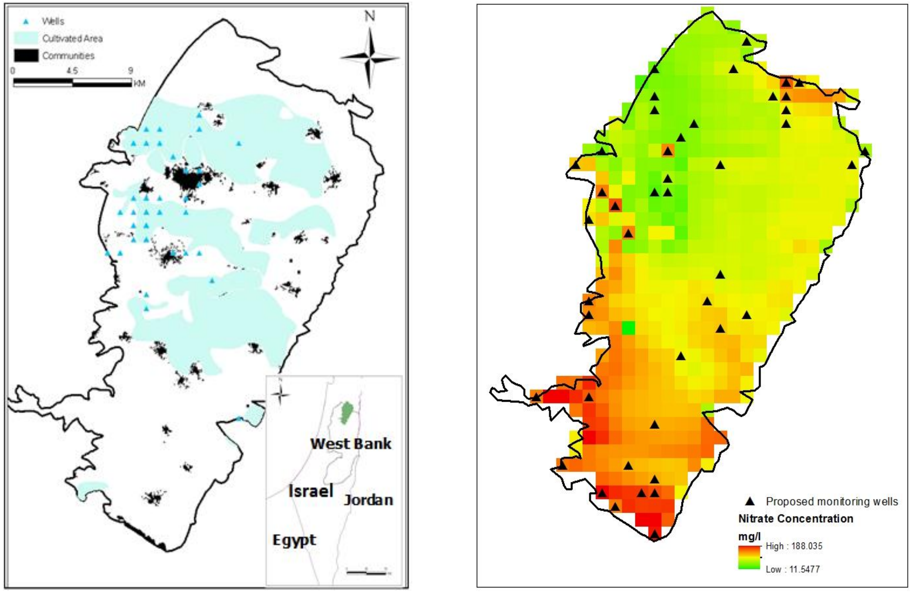

Fig. 2. Eocene Aquifer study area. (Left) Palestinian communities, abstraction wells, and cultivated areas. (Right) Average nitrate concentrations predicted by Monte Carlo simulations and proposed monitoring well locations.

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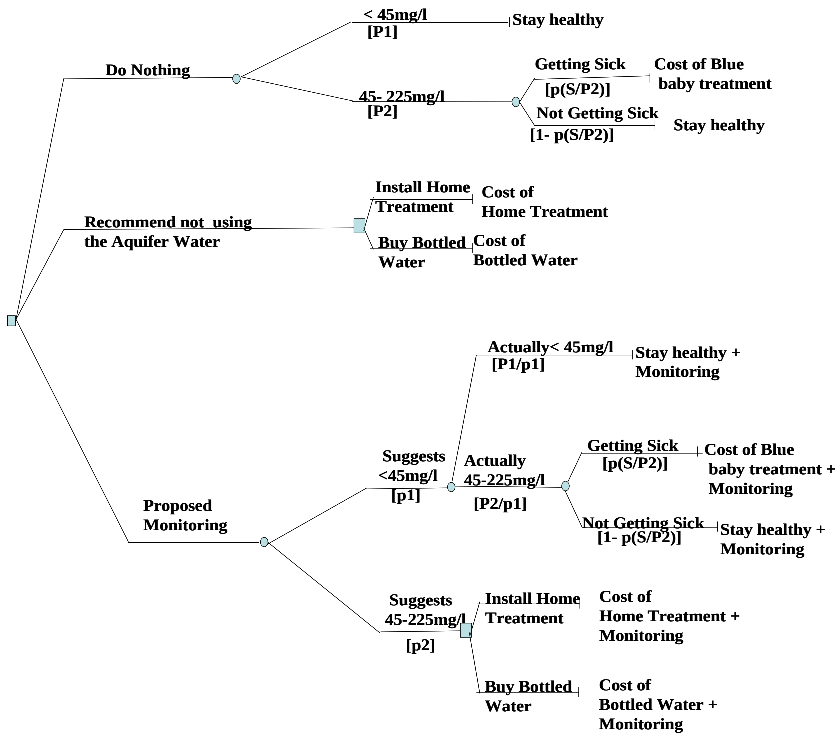

Fig. 3. Decision tree model for the scenario where people fully abide with decision maker recommendations.

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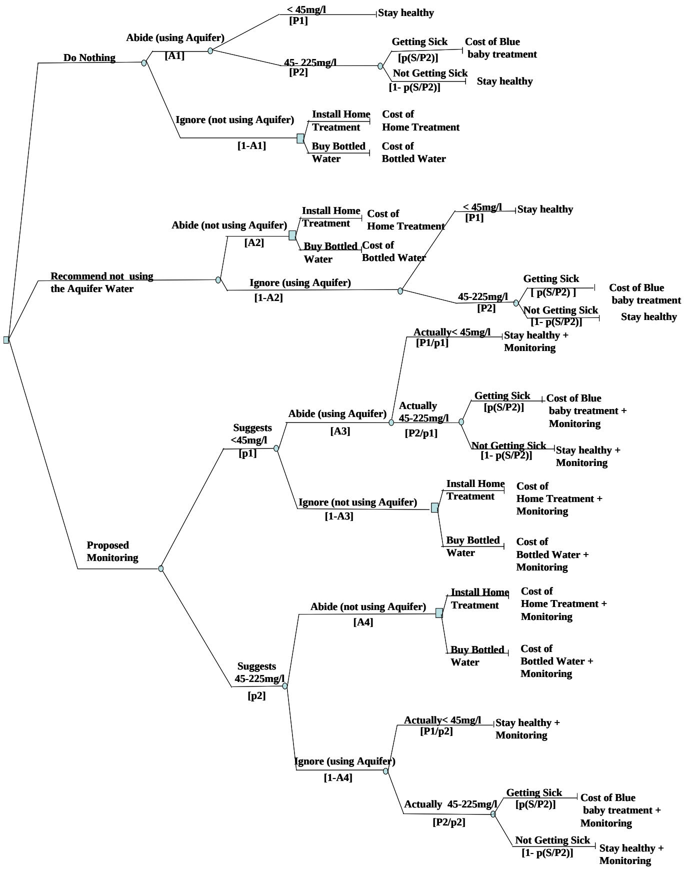

Fig. 4. Decision tree model for the scenario where some people abide with, and others ignore decision makers' recommendations.

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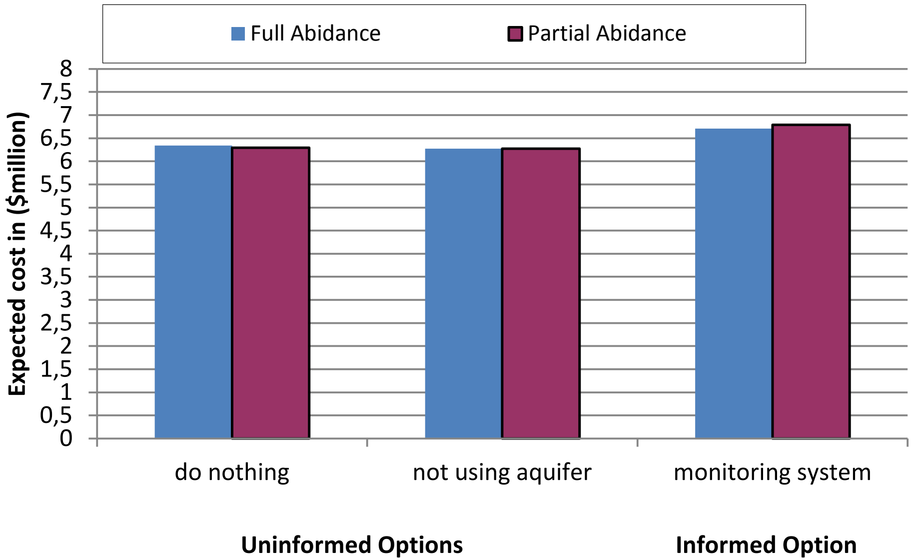

Fig. 5. Present-value, expected costs of alternatives.

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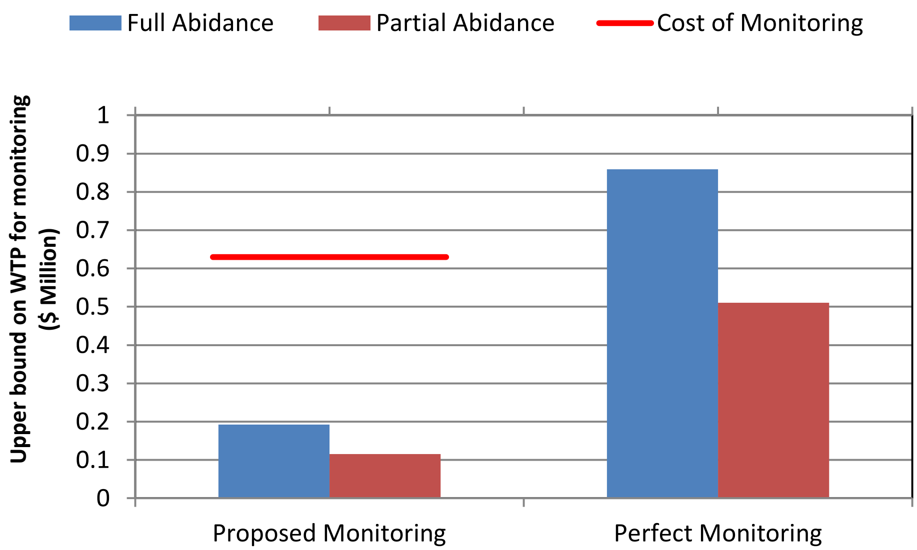

Fig. 6. Upper bounds on willingness-to-pay for monitoring systems.

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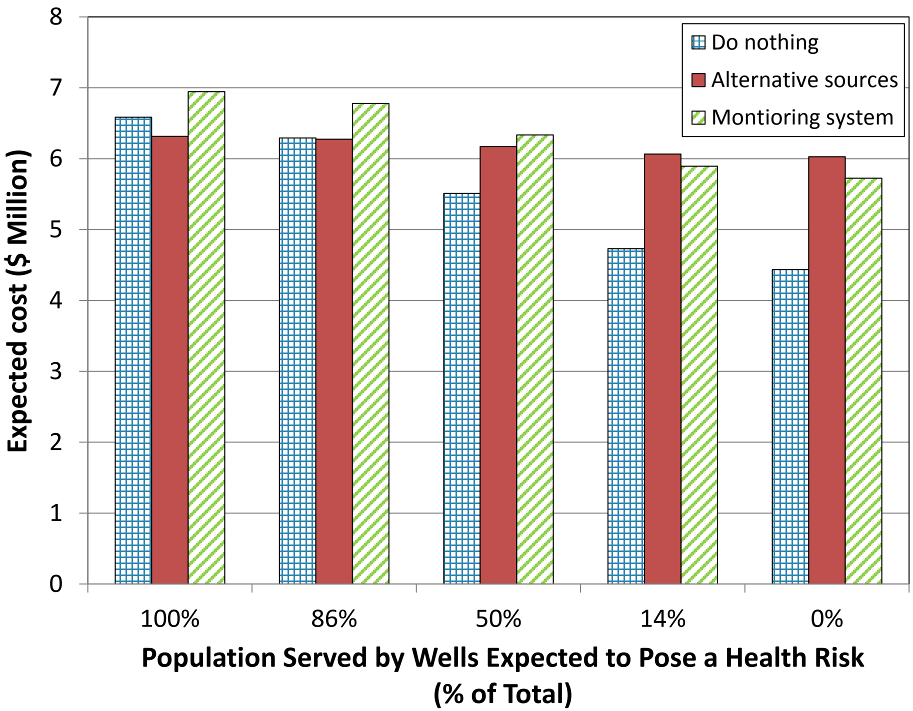

Fig. 7. Expected costs for alternatives with partial abidance under population redistribution scenarios where more/less people use nitrate-contaminated aquifer water.

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