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INFORMATION SYSTEMS FACILITATING GROUNDWATER SUSTAINABILITY MANAGEMENT

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INFORMATION SYSTEMS FACILITATING GROUNDWATER SUSTAINABILITY MANAGEMENT

ABSTRACT

Groundwater resources are a major source of drinking water and increasingly require management to be sustained. Achieving this requires Information Systems (IS) supporting the revelation of contamination information from data obtained via monitoring projects. For effective contamination control, its type, size, structure and degree must be unveiled. Unfortunately, when contamination occurs such holistic information is not readily available from monitoring data. Monitoring groundwater quality is limited to specific locations, namely the monitoring wells. Hence, from limited and fragmented data, contamination information must quickly be implied. This study analyzes alternatives of designing IS to facilitate contamination control from the limited sources of data. For this purpose we analyze the monitoring process and different methodologies for data collection from monitoring wells. We have analyzed the efficiency of the various methods with an aquifer domain comprising a small part of the Coastal Plain Aquifer (CPA) of Israel. The results suggest that systematic sampling approaches are the most efficient for attaining sustainability goals.

Keywords

sustainability, decision processes, fragmented data, groundwater quality monitoring, aquifer pollution control, contamination identification.

INTRODUCTION

In most semi-arid regions the major source of water for the population is groundwater. Water supply wells are required to provide sufficient quantities of water with good quality, while preserving this source of water from deterioration. It means that sustainability of groundwater resources is crucial in these regions, as most needs of water in such areas are provided by water supply wells. However, in many semi-arid regions, due to industrial and agricultural technology development the groundwater quality is continuously decreasing.

Achieving groundwater resources sustainability is subject to effective decision making. An important process in this context, is deciding on measures to be taken to avoid spreading of pollutants that occasionally and/or accidentally penetrate into the aquifer. This process is complex as various measures can be taken. The effectiveness of each measure varies according to the type of the aquifer, contaminating species and the pollution degree.

While technology supporting quality monitoring is available, Information Systems (IS) aiming to support groundwater resources sustainability have been underdeveloped. Perhaps the reasons lie in the so far limited involvement of the IS community in environmental sustainability research. Water sustainability problems call for IS input. While quality assurance may be achieved from simple monitoring data, sustainability demands more than technology alone; it demands efficient input for decision processes and actions. In this aspect, the groundwater sustainability problem is very much an IS problem. That is, the processes, software, and information technologies do not appear to efficiently support individual and societal goals (Watson et al. 2010).

In this study we consider the societal goal of groundwater resources sustainability. We analyze how IS can help form the information to support efficient and timely decision making for dealing with groundwater pollution.

In order to provide guidelines for IS supporting groundwater resources sustainability we look into methods of quality monitoring, and controlling the spread of contaminants in aquifers. We identify the processes that are useful for gathering data for decision making at different levels. Further, we analyze the information that is needed to control the contamination of groundwater. Based on this, we analyze different approaches for data gathering. We examine which approach can optimally support information forming that may be applicable for decision processes aiming at the control of contaminant spreading in aquifers and preservation of groundwater quality.

This paper incorporates several sections that allow the reader following the notion of the general topic of groundwater resources sustainability and its need for proper IS involvement. In Section 2 we review the monitoring processes associated with groundwater quality assurance. In Section 3 we analyze how the monitoring process may serve as input for decisions about sustainability. Section 4 integrates our findings obtained in preceding sections. In this section we analyze different monitoring methodologies and methods that may support efficient identification of types of contaminants and their sources, which may risk the sustainability of the groundwater resources. In Section 5 we discuss our results. Finally, Section 6 provides summary and conclusions, which are relevant to sustainability of groundwater resources..

MONITORING DATA

Information systems to support groundwater quality monitoring have long been around (e.g. Raghav et al 2010). Groundwater quality monitoring is usually done by collecting water samples from monitoring wells and mainly from water supply wells. In general, the number of water supply wells in a semi-arid region is large. Therefore, monitoring the quality of groundwater is commonly carried out by successive steps of selecting a small number of sampled wells. While sampling all wells will provide the most accurate result, such a method is not cost efficient since sampling procedures are costly. Further, if all wells are constantly sampled, redundancy in monitoring results is likely to occur.

Therefore, as mentioned, quality monitoring is done progressively across time. That is, at each step in time, different groups of wells are selected for contamination testing. Different parameters of the water supply wells may guide in selecting the sampled group of wells at each sampling step, like:

1) The well's concentration of contaminants. A variety of contaminants may be considered, these may include various anions, like chloride and nitrate and cations, like heavy metals, various types of volatile organic compounds (VOCs), like chlorinated hydrocarbons, etc. In this study we refer to chloride as the contaminant, whose concentration (C) may be higher than an adopted threshold value for drinking water.

2) The well's partial regional discharge (Qp). This parameter represents the partial amount of water per unit time that is supplied from the well to the water supply system.

3) The well's contamination flux (QpC). This parameter represents the partial amount of contaminant per unit time that is supplied from the well into the water supply system.

4) The physical location of the well, i.e. the wells' coordinates, is an important parameter for considering its selection for sampling.

Monitoring groundwater quality comes for assuring the adequate water supply to water consumers. Under this objective the wells best selected for sampling are typically those that help to identify pollution in the supplied water. However, the selection methods for quality control do not consider other decision processes that may take place in the domain. The results of the groundwater quality monitoring can also provide input to decisions about possible measures leading to sustainability of the groundwater resources.

MONITORING DATA AS INPUT FOR ATTAINING SUSTAINABILITY

Water Resources Sustainability Goals

When considering the water resources sustainability goal, the objective of the well sampling process goes beyond simple quality assurance. Under the sustainability goal, there is also e.g., the need to avoid spreading of contaminants in the aquifer. Different measures can be taken to avoid such spreading. The appropriateness of the measure depends on the pollution degree and economic calculations. Implemented measures may incorporate decreasing pumping rates of groundwater, using various types of barriers (Rubin et al. 2010), aquifer remediation (Chu et al. 2006), surface runoff recharge (Vondrak et al. 2008), wastewater recycling for consumers like agricultural crop irrigation and the industry (Clopeck 2006), and production of drinking water by desalination of brackish and sea water (Riverol-Cañizares and Pilipovik 2010).

Deciding on the measure to be taken requires calculations referring to stochastic natural processes of groundwater recharge, as well as man made processes of pumping and artificial recharging of the aquifers. Primarily adequate calculations of mass balances of water quantities and fluxes of contaminants should provide forecasting results regarding continuing regional uses of groundwater. These results can provide guidance for implementing measures aimed at changing groundwater uses in order to assure sustainability of the limited available groundwater resources. Therefore, the pollution degree and pollutant distribution in the domain comprise critical input information for following decision processes aiming at the water resources sustainability. This information can only be formed from the data on isolated contamination levels. That is, the contamination information is formed from data gathered in the monitoring process. The information needed can be classified as follows:

1) The contaminant distribution in the aquifer and possible locations of contaminant sources,

2) The potential risk of contamination of the most productive wells,

3) The total contaminant flux introduced into the regional water supply system via the water supply wells of the domain, and

4) The wells with high contaminant concentration, possibly concentration larger than an adopted threshold value. Such wells can be used as hydraulic barriers (Rubin et al. 2010) and the water of which should be treated.

That is, the monitoring process may provide input data to decision processes dealing with preserving and protecting the available groundwater resources.

Basically, we may classify the objectives of the water sustainability decision process into two classes:

1) Short time range objectives, and

2) Long time range objectives.

The first class concerns the quickest and most accurate way of identifying most important parameters connected with groundwater pollution during a time period of several months. The second class concerns following up changes. This study originates from short time range objectives.

The major characteristic of short time range monitoring is the minor changes in parameters of the regional aquifer flow and contaminant distribution. It means that piezometric heads (water table), wells' discharges and distribution of contaminants are subject to insignificant changes during the time period in which the monitoring project is implemented. Under such conditions, carrying out the selection of sampled wells in each sampling step is an issue of environmental statistics (Gilbert 1987). The efficiency of well selection according to some simple procedures can be obtained by calculations based on statistical analysis. On the other hand, more sophisticated procedures and/or approaches, whose efficiency analysis is complicated, call for carrying out numerical simulations preferably referring to practical examples and major objectives of the monitoring project.

Data Selection Approaches

Alley (1993) has reviewed and extended environmental monitoring procedures suggested by Gilbert (1987) for monitoring groundwater quality. Basically, the different methods described by Gilbert (1987) and Alley (1993) refer to short time range of groundwater quality monitoring and are based on applying two types of methodologies: 1) Random selection of sampled wells, and 2) Systematic selection of sampled wells.

According to the simple random selection, in each sampling step n pumping wells are randomly selected from a total number of N regional wells by applying a proper algorithm. In general the n selected wells are drawn successively without replacement. It means that once a well has been selected in a sampling step it is not selected in following sampling steps. Random selection with replacement allows selecting sampled wells in all or some following sampling steps. The random selection of sampled wells can be carried out by referring to a single unit domain or a domain divided into some sub-domains from which wells are randomly selected according to some rules. As an example the sub-domains may be represented by rectangular blocks comprising a grid (Choquette and Katz 1989). It is possible to refer to sub-domains incorporating clusters of wells, which are identified in the region.

Shlomi et al. (2010) advocate applying a utility function of selecting the wells in each sampling step from a grid of rectangular blocks. However, this study does not provide guidelines for properly defining the utility function and the optimal options of using wells' selection according to values of the well utility function. Various studies concerning different issues and objectives of groundwater quality monitoring have also been conducted. Some of those studies raise several important points relevant to this study, as shown in this paragraph. The study of Schmidt (1977) concerns the redundancy of water quality results obtained via a series of samples from a single well, even under conditions defined as "steady state". This issue should definitely be taken into account in cases of practical well sampling. However, our study is not involved with possible redundancy of the water quality data. The study of Grosser and Goodman (1985) concerns the methodology of groundwater sampling frequencies aiming at following possible changes in groundwater quality. This issue is relevant to long time ranges of monitoring. The study of Lee and Kitanidis (1996) concerns issues associated with optimization of monitoring well installation time and location during aquifer decontamination. Again these issues are relevant for following changes of groundwater quality in an aquifer subject to remediation and are not incorporated with the scope of this study. The study of Mogheir and Singh (2002) concerns the application of information theory to groundwater quality monitoring network, which are not concerned in the present study that refers to the objectives of short time range monitoring of groundwater quality.

INTEGRATION – FORMING INFORMATION FOR WATER SUSTAINABILITY DECISIONS

Conceptual Model of the Decision Process

The conceptual model of the monitoring and sustainability preserving processes, taking place in the context of groundwater resources management, is shown in Figure 1. The area above the horizontal line in the figure depicts the monitoring process. The area below the horizontal line shows how data from the monitoring process may help form information for attaining groundwater resources sustainability. The figure shows that when considering water sustainability, more information is required for the decision processes and therefore selection of wells for monitoring becomes more important. Some of this information is external to the monitoring system, like information about water usage parameters in society. However other types of information are formed in the system – namely, contamination flux, risk to productive wells, wells with high contamination levels, and contaminant distribution in the aquifer. The figure shows that different sampling procedures may guide the monitoring process in order to help form this information.

With the conceptualization at hand, we turn to examine the monitoring procedure under the sustainability frame of reference. We adopt several basic concepts, which may provide guidelines for adopting the optimal methods for achieving sustainability based on data of short time scale groundwater monitoring. We examine the efficiency of the methods in forming the necessary information for contamination control decision making.

In section 3.2 we have identified two general methodologies of successive steps of selecting n sampled wells from a population of N wells. Each one of these methodologies can be associated with a particular method of referring to the regional domain of interest:

1) The whole domain is considered as a single unit,

2) The domain is covered by a grid of small rectangles (blocks), and

3) The domain is divided into several sub-domains incorporating clusters of wells,

Many experimental simulations carried out in this study have indicated that in most cases referring to the last option is the most efficient. However, adequate guideline for the sampled well selection should be provided in connection with major objectives of the monitoring project.

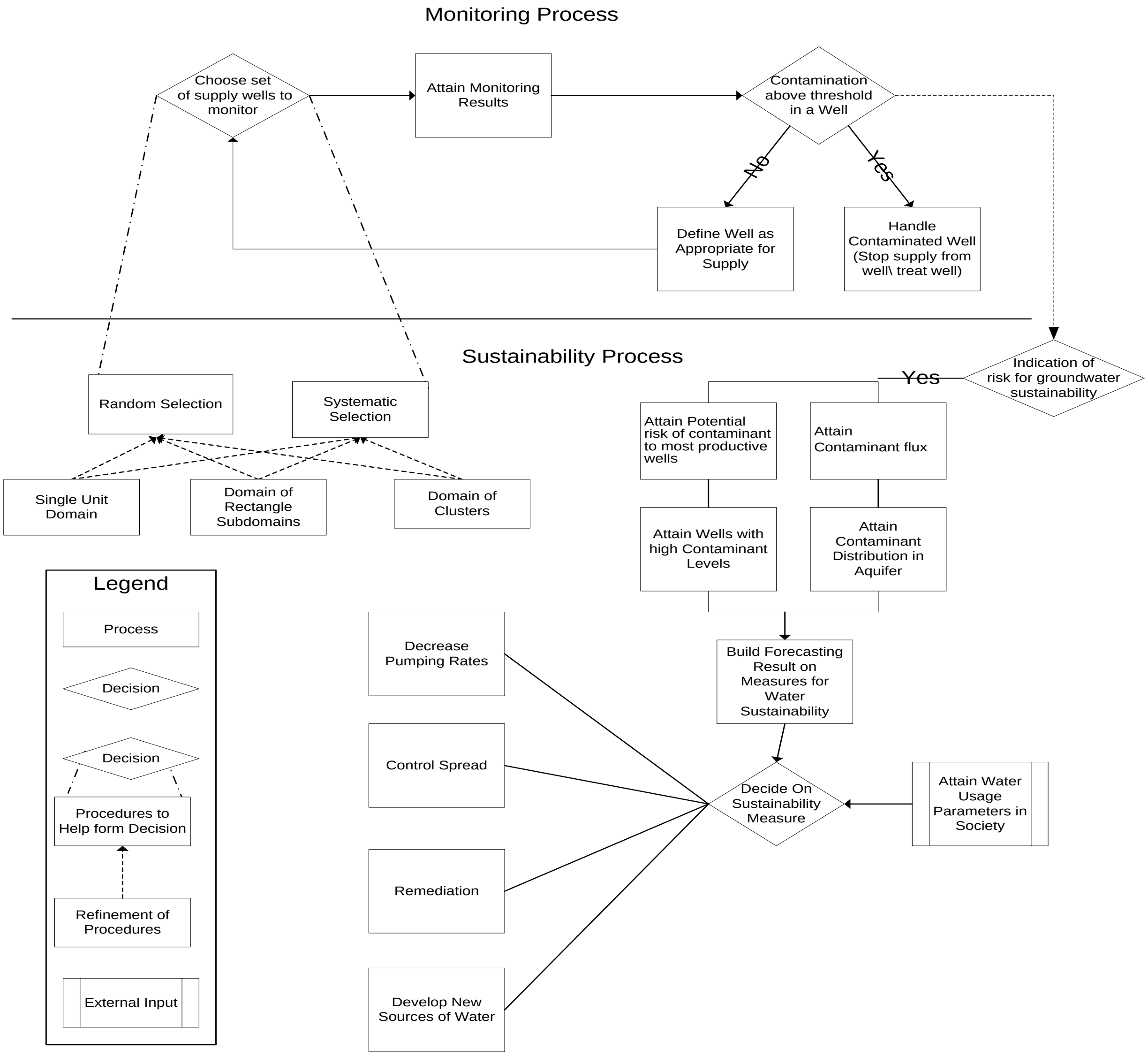

Figure 1. The conceptual model of quality monitoring and groundwater resources sustainability

Analysis

Data

In order to test the efficiency of the considered two methodologies and different methods of selecting the sampled wells in each sampling step we refer to a small area of 5 × 4 km2 of the Coastal Plain Aquifer (CPA) in Israel south of Tel-Aviv, in which 63 water supply wells are located. From the Water Authority of Israel we have gotten the coordinates of the wells and their annual water production (discharge). On the other hand we could get only sketchy information about contaminant concentrations in these wells. The different types of information indicate that chloride (which is the contaminant referred by this study) concentration is continuously increasing, and the water supply wells are subject to risks of chloride concentrations, which are larger than an adopted threshold value of 300 ppm. Therefore, we refer to a hypothetical case of 63 regional water supply wells whose distribution in the domain is graphically shown in Figure 2. Besides the water supply wells there are 4 monitoring wells at the 4 corners of the domain.

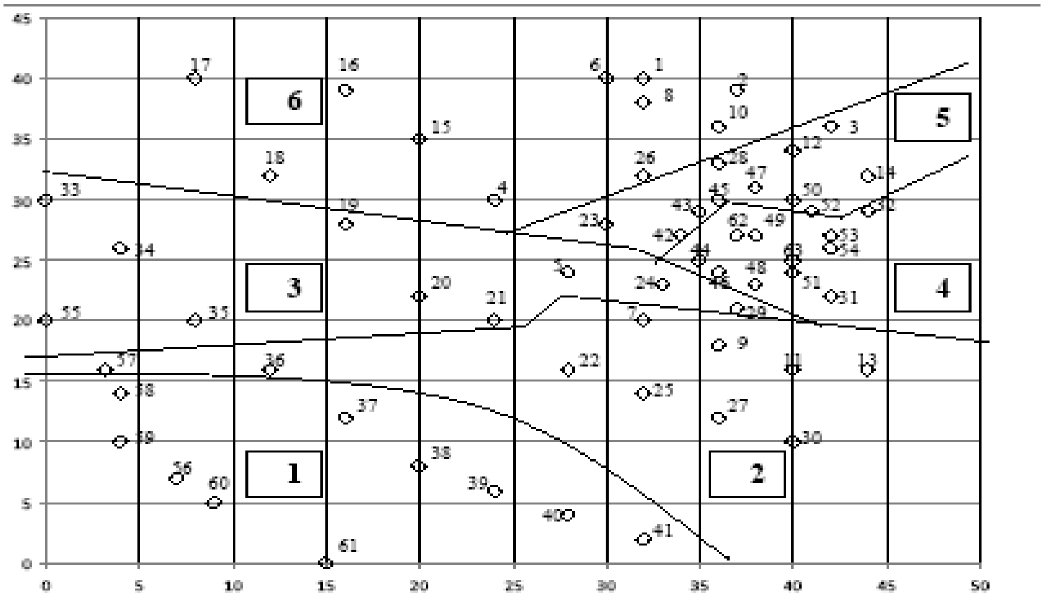

Figure 2. The tested domain with 63 water supply wells divided into 6 clusters

Figure 2 shows one of the options tested by this study of dividing the domain into 6 clusters of wells. The choice of these clusters originates from considering the proximity of the wells. However, we may choose other options like a larger number of well clusters and/or different wells incorporated within particular clusters. The choice of the well cluster format should depend on the general planning of carrying out the selection of the sampled wells, and possibly some extra information that is available to the planners of the well sampling project. We have chosen to select 6 sampled wells in each sampling step. Therefore, in cases of wells selected from this number of clusters of wells, in each sampling step a single well is selected for sampling from each cluster of wells, and during the last sampling step only 3 wells are sampled.

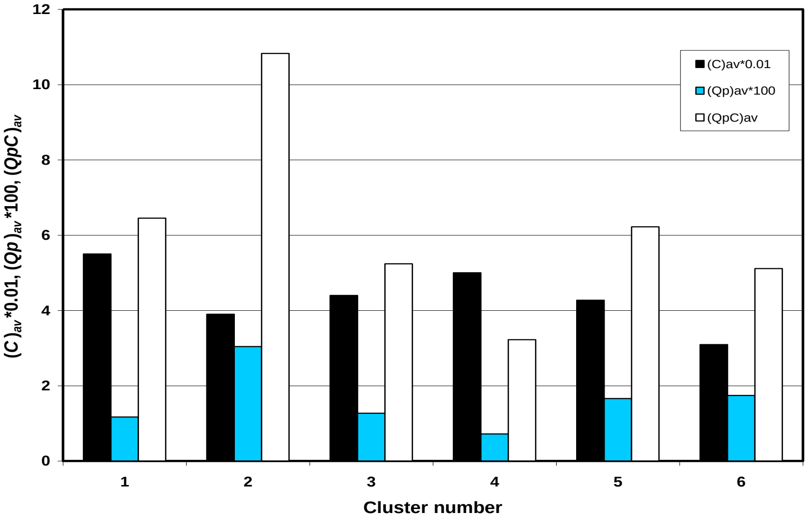

Figure 3. Values of (C)av, (Qp)av and (QpC)av of the 6 well clusters

Figure 3 shows the differences between values of (C)av, (Qp)av and (QpC)av of the 6 well clusters. This graphical presentation of the well cluster parameters indicates that choosing a well utility function identical with the chloride concentration, or discharge, or chloride flux of the well as a basis for selecting the sampled wells may lead to results that are not necessarily optimal for quick reproduction of the average values of all these parameters for the entire domain.

Random selection methodology

Initial conditions for the sampled well selection are determined by measuring chloride concentration in water samples taken from 4 monitoring wells, which are located at the 4 corners of the domain, and are not shown in Figure 2. Therefore, selecting sampled water supply wells starts with an approximate distribution of chloride in the domain. However, this initial chloride distribution has no effect on well selection according to the methodology of random selection of sampled wells. We represent here results of testing two methods of random selection of sampled water supply wells:

1) 6 wells are randomly selected in each sampling step, while referring to the entire domain as a single unit, and

2) A single well is randomly selected from each cluster of wells in each sampling step.

Systematic selection methodology

For the systematic methodology of selecting sampled water supply wells in each sampling step we have applied a well utility function, *U* and tested several general definitions for this function:

1) The well utility function is identical with the partial discharge of the well, namely:

$$U = Q_p \tag{1}$$

This method of sampled well selection emphasizes the need for water quality information in most productive water supply wells, which is considered as the major objective of the groundwater quality monitoring project. It should be noted that in this case the well utility functions of all wells are not affected by the information about the domain, which is accumulated in the preceding sampling steps.

2) The well utility function is identical with the chloride concentration of the well, as obtained during the last sampling step, namely:

$$U = C \tag{2}$$

This method emphasizes the need for information about sources of chloride in the domain and water supply wells with highest chloride concentrations. In this case the accumulated information about chloride distribution in the domain leads to changes in values of *C* in wells that have not yet been sampled.

3) The well utility function is identical with the product of the well partial discharge by its chloride concentration, namely:

$$U = Q_p C \tag{3}$$

This method emphasizes the need for information about major fluxes of chloride with pumped groundwater. In this case the accumulated information about chloride distribution in the domain leads to changes in values of Q_pC in wells, as occurred with the parameter *C*.

4) The well utility function is based on a linear combination of the well utility functions represented in preceding paragraphs, namely:

$$U = a_1 Q_p + a_2 C + a_3 Q_p C \tag{4}$$

where

$$\sum_{i=1}^{3} a_i = 1 \tag{5}$$

However, there are differences of some orders of magnitude between values of Q_p, *C* and Q_pC; therefore, identical weights of the different terms comprising the utility function of Eq. (4) imply differences of orders of magnitude between values of the coefficients a_i.

RESULTS

This section of the manuscript represents some important results of the many numerical simulations performed within this study. These results provide a guideline that may be adopted for designing IS so that the right data would be used to efficiently present information relevant for attaining sustainability.

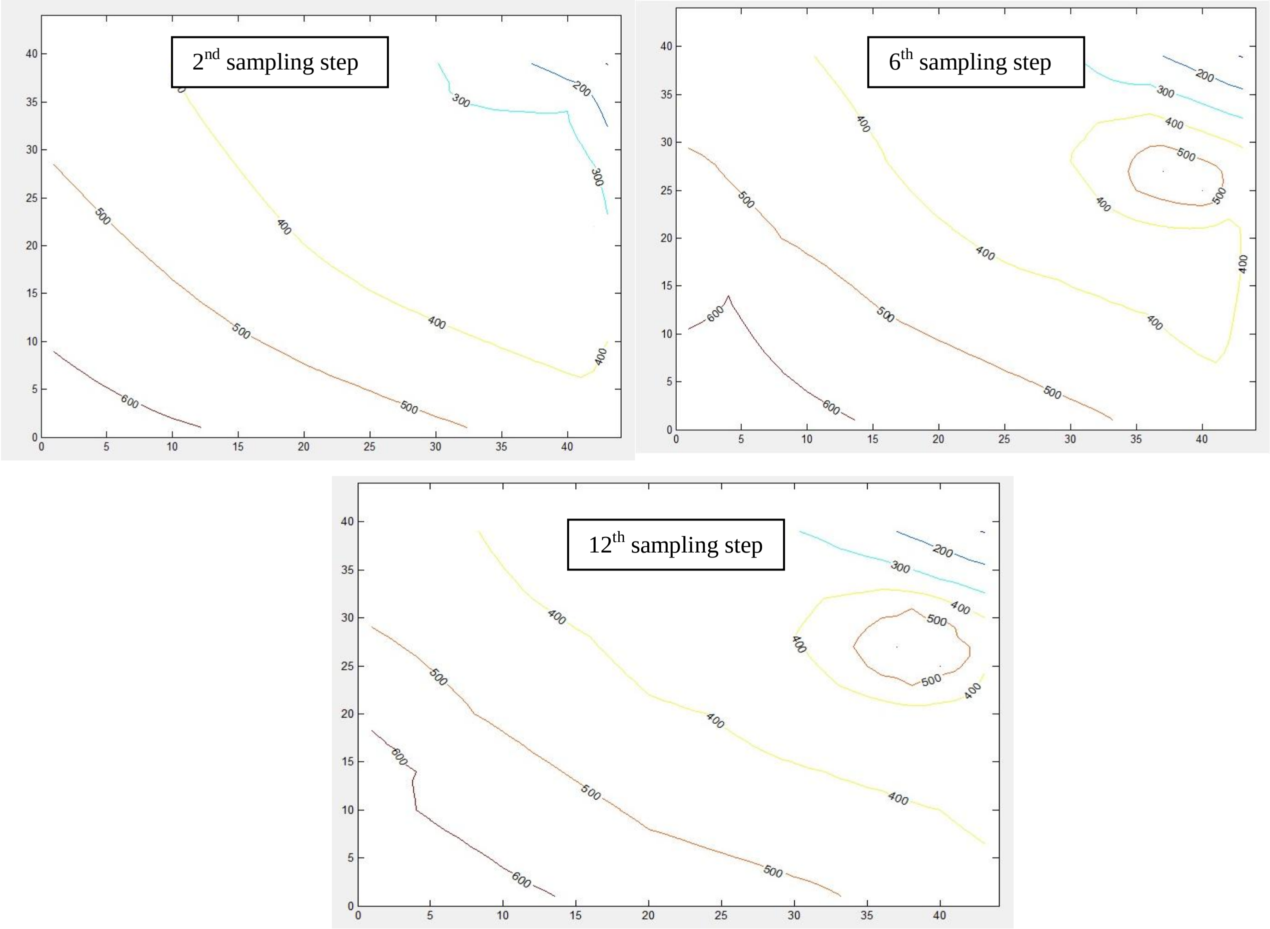

Figure 4. Chloride concentration distribution obtained after the 2nd, 6th and 12th steps of the sampled wells' selection (U = Qp, 6 well clusters, 6 water supply wells are sampled in the 2nd – 11th sampling steps, 3 wells are sampled in the 12th sampling step)

We have examined which monitoring method can support contamination handling decision making most efficiently. For this purpose we have identified monitoring methods that help form most quickly and accurately the information required for the decision maker. We first look into the production of information about contaminant distribution in the aquifer and possible locations of contaminant sources. Figure 4 provides an example of gradually achieving an adequate description of the chloride distribution in the domain. This figure has been obtained by applying the method of assuming U = Qp with a domain divided into 6 clusters of wells.

According to Figure 4, the 2nd step of sampled wells' selection (which is the 1st step of sampling water supply wells) shows gradual decrease of the chloride concentration from the bottom left corner of the domain towards the top right corner of the domain. No clear information is provided about any possible local source of chloride in the domain. On the other hand the 6th step of sampled wells' selection shows gradual decrease of the chloride concentration from the bottom left corner of the domain towards the top right corner of the domain. However, this sampling step also provides clear information about a local source of chloride in the domain, which is surrounded by the closed contour of 500 ppm. It is also evident that the differences between results of the 6th and 12th sampling steps are not significant, and achieving the information about possible local sources of chloride in the domain and the location of such sources is roughly obtained after carrying out around 6 steps of sampled wells' selection. The results of quite good reproduction of chloride concentration in the domain after 6 steps of sampled wells' selection, as shown in Figure 4 concern the example of the well utility function U = Qp while the domain is divided into 6 clusters of wells from which 6 water supply wells are sampled during each sampling step. However, approximate achievement of the chloride distribution reproduction after around 6 sampling steps has also been obtained by using the other methods tested in this study.

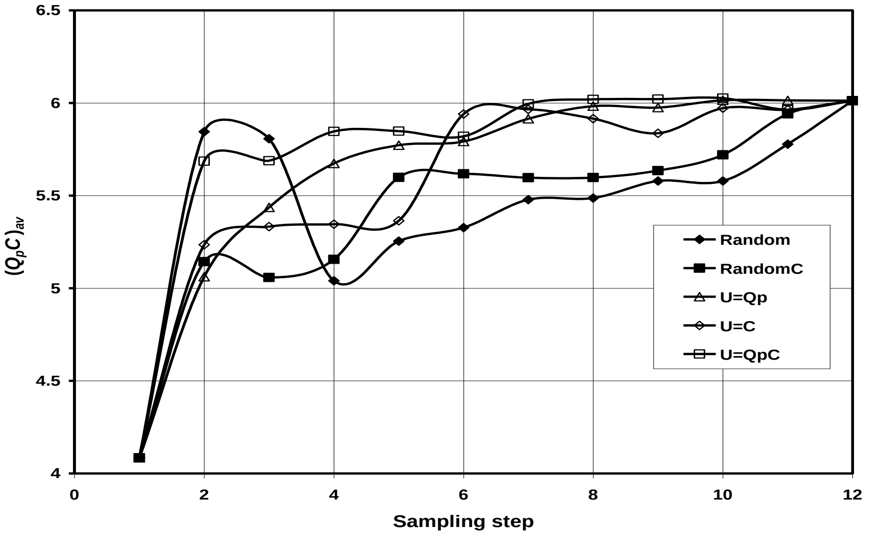

Figure 5. The convergence of (QpC)av -values during the successive steps of sampled wells' selection (Random = random selection with reference to a single unit domain; RandomC = random selection with reference to a domain divided into 6 clusters of wells; U = selection of wells based on the application of 3 different options of well utility function)

In the next stage we have looked into the efficiency in producing information about the total contaminant flux introduced into the regional water supply system via the water supply wells of the domain. Figure 5 represents the convergence of values of (QpC)av of the water supply wells of the domain. Results of the random selection methodology vary around some average values. However, Figure 5 indicates that generally random selection of wells provides results of inferior quality than methods, which apply the well utility function. With regard to the parameter (QpC)av results of the random selection of wells from a single unit domain are inferior to those obtained from a domain divided into 6 clusters of wells. From the different methods of applying a well utility function, the method of U = QpC provides the true value of (QpC)av after the 6th sampling step, and looks superior than other methods in all other sampling steps.

We now turn to examine the efficiency in forming information about the wells with contaminant concentration larger than an adopted threshold value. Figure 6 represents the variation of the number (Nc) of water supply wells with chloride concentration larger than an adopted threshold value of 300 ppm.

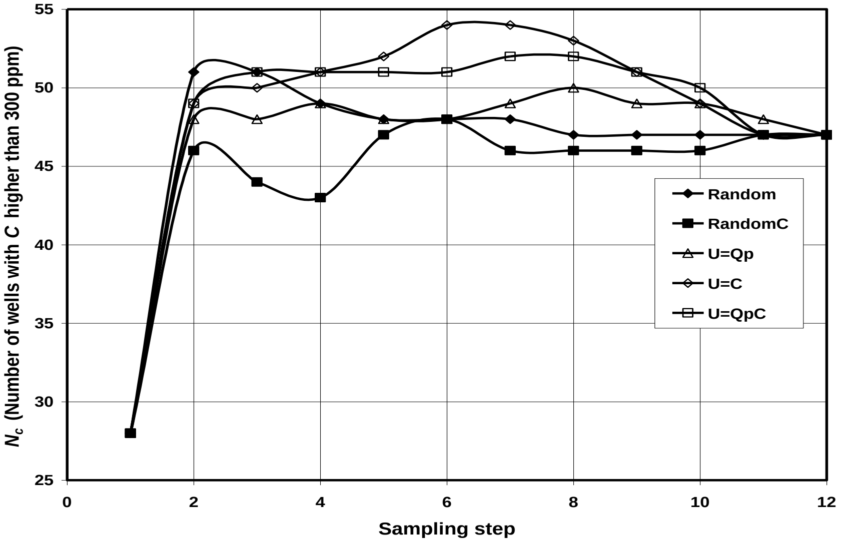

Figure 6.The convergence of N_c- values during the successive steps of sampled wells' selection (Random = random selection in a single unit domain; RandomC = random selection in a domain divided into 6 clusters of wells; U = selection of wells based on the well utility function)

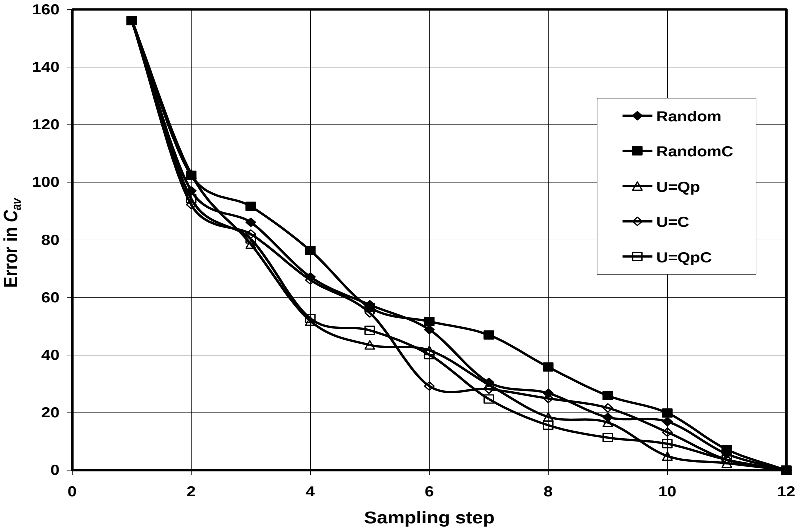

Figure 7. The decrease of error in values of Cav during the successive steps of sampled wells' selection (Random = random selection in a single unit domain; RandomC = random selection in a domain divided into 6 clusters of wells; U = selection of wells based on the well utility function)

Figure 6 indicates that generally the random selection of wells provides results of inferior quality than methods of systematic well selection. Again the random selection of wells from a single unit domain is inferior to selection from a domain divided into 6 clusters of wells. From the different methods of applying a systematic well selection based on using the well utility function, the method of U = Qp provides the true value of Nc after the 5th sampling step, and looks superior than other methods in all other sampling steps. However, obtained values of Nc are subject to oscillations, and also there are changes in the particular wells incorporated with the value of Nc after each sampling step. Finally, Figure 7 represents the efficiency of forming information about contamination in the water supply wells. This figure shows the decrease of values of the error in Cav of the water supply wells of the domain. Also in this case results of random selection of wells from a single unit domain are inferior to those obtained from a domain divided into 6 clusters of wells. From the different methods of applying a well utility function, the method of U = C provides the minimum value of error in Cav after the 6th sampling step, but in all other sampling steps the well utility functions U = Qp and U = QpC provide smallest values of this error.

SUMMARY

In this study we have examined how processing monitoring data can support efficient decision making about contamination control. We have discussed the groundwater monitoring domain, as well as the contamination control decision processes. Information required for groundwater resources sustainability decisions has been identified, like: a) Portraying contours of contaminant distribution in the domain and risk of water supply wells contamination, b) Contaminant concentration in most productive wells, c) The flux of contaminant into the water supply system, and d) Wells with contaminant concentration higher than an adopted threshold value. The efficiency in forming the information from monitoring data has been examined and tested. The groundwater monitoring projects considered by this study refer to a short time scale in which successive sampling of a small number of water supply wells should gradually provide the required information. Such projects can be carried out according to 2 general methodologies: a) Random selection of sampled wells in each sampling step, and b) Systematic selection of the sampled wells.

For the systematic methodology of selecting sampled wells we have applied methods of dividing the domain into clusters of wells whose number is identical with the number of wells selected for sampling in each step of sampled wells' selection. Other methods like dividing the domain by grids incorporating rectangular blocks have been found inefficient in cases of non-uniform distribution of wells in the domain.

Our tests of the different methods of sampled wells' selections have indicated that in general systematic selection methods are more efficient than methods of random selection of sampled wells. However, adoption of parameters guiding the systematic selection of sampled wells should be carried out in connection with the major objective of the groundwater quality monitoring project.

This study contributes by conceptualizing the decision making processes in groundwater monitoring and quality control. The study has also paved the way for developing IS to effectively support groundwater sustainability decision processes. While the study is associated with groundwater sustainability, we believe the results and water quality parameters of this study can be useful for developing guidelines for carrying out monitoring and sustainability projects in general.

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