UNIVERSITI PUTRA MALAYSIA

GROUNDWATER QUALITY ASSESSMENT AND OPTIMIZATION OF MONITORED WELLS USING MULTIVARIATE GEOSTATISTICAL TECHNIQUES IN AMOL-BABOL PLAIN, IRAN

TAHOORA SHEIKHY NARANY

FPAS 2015 11

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By

TAHOORA SHEIKHY NARANY

Thesis submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfillment of the Requirements for the Degree of Doctor of Philosophy

March 2015

DEDICATION

This work is dedicated to my sweet and loving family, specially my
Mother & Father
Whose affection, love, encouragement and prays of day and night make me able to get such success and hono

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March 2015

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Groundwater plays an essential role for human, animal, and plant life as well as an indispensable resource for the economy, especially in arid and semi-arid region. Appropriate monitoring strategies are required to assess the conditions of groundwater quality in the aquifer system, prevention of a potential threat to human health, and measurement of the efficiency of water protection. The main aim of this study is to assess and redesign the information-cost-effective groundwater monitoring network using geostatistical techniques in Amol-Babol Plain, Iran. The integration of multivariate statistical methods with geostatistical interpolation techniques revealed that salinity and total and faecal coliforms as time independent variables and hardness as a time dependent variable influenced the groundwater quality in the study area. The graphical geochemical analyses justified that the groundwater types vary from fresh water type in the west and south sides, to brackish-saline water type in central and eastern sides, and to saline water on the north-eastern area. Hydrogeochemical investigation revealed that evaporation/precipitation and dissolution of carbonate minerals as dominant factors, which control groundwater salinity and hardness in the study area, respectively. Since the agricultural lands cover more than 80% of the plain, the newly devised GIS-Index integration approach was proposed in order to identify the suitability of groundwater for irrigation usage and to determine suitable zones for irrigation activities based on the irrigation water quality index (IWQ) and hydrogeological factors. The index approach shows that more than 90% of the total study area has good to excellent suitability condition for irrigation purpose. Groundwater quality assessment based on the data obtained from arbitrary sampling wells might be presented redundant or shortage of information. Therefore, monitoring network wells should be optimized in information-cost-effective way, based on the current groundwater quality data and vulnerability of aquifer to contamination. DRASTIC model was applied as a vulnerability assessment method based on the physical environmental aquifer parameters for assessing potential risk zone of aquifer to contamination, which showed more than 88% of the total area was classified as low to

moderate risk to pollutant. A new optimization approach was proposed for redesign monitoring network wells using optimization algorithm based on the vulnerability of aquifer to contaminations, estimation error of sampling wells, nearest distance between wells, and source of contamination in the study area. Application of mass estimation error revealed that 100 and 74 sampling wells are suitable scenarios for monitoring natural and anthropogenic contaminant, respectively. Combination of the selected scenarios in GIS showed that contaminant mass detection capacity of around 86% can be obtained from 114 sampling wells, instead of 154 initial sampling wells.

Abstrak thesis yang dikemukakan kepada senate Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

PENILAIAN KUALITI AIR BAWAH TANAH DAN PENGOPTIMUMAN TELAGA PEMANTAUAN MENGGUNAKAN TEKNIK MULTIVARIAT GEOSTATISTIK DI DATARAN AMOL-BABOL, IRAN

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Air bawah tanah memainkan peranan penting kepada manusia, haiwan dan juga tumbuhan yang merupakan sumber utama kepada ekonomi, terutamanya di kawasan semiarid dan arid. Strategi pemonitoran yang sesuai diperlukan untuk menilai keadaan kualiti air bawah tanah didalam sistem akuifer, menghalang potensi ancaman kepada kesihatan manusia, dan pengukuran kecekapan pelindungan air. Tujuan utama kajian ini untuk menilai dan mereka semula jaringan pemonitoran air bawah tanah yang cekap dari segi maklumat dan kos menggunakan teknik-teknik geostatistik di Dataran Amoi-Babol, Iran. Integrasi analisis pelbagai varian (ANOVA) dua dengan teknik interpolasi geostatistik menunjukkan saliniti, dan jumlah koliform tinja merupakan pembolehubah bebas masa dan keliatan merupakan pembolehubah kadar masa mempengaruhi kualiti air bawah tanah di kawasan kajian. Analisis grafik geokimia menunjukkan variasi jenis air bawah tanah daripada jenis air tawar di bahagian barat dan selatan, kepada air payau di bahagian tengah dan timur kepada air masin di bahagian timurlaut. Penyiasatan hidrogeokimia menunjukkan peruwapan dan presipitasi, dan pelarutan mineral karbonat sebagai faktor dominan yang mengawal saliniti dan keliatan di kawasan kajian. Oleh kerana kawasan pertanian merangkumi lebih daripada 80% daripada dataran ini, pendekatan integrasi indek GIS yang baru dicadangkan untuk mengenalpasti kesesuaian air bawah tanah, dan untuk penentuan zon sesuai untuk aktiviti pengairan berdasarkan indek kualiti air pengairan (IWQ) dan faktor hidrogeologi. Pendekatan indek menunjukkan lebih daripada 90% kawasan kajian mempunyai keadaan kesesuaian yang cemerlang untuk kegunaan pengairan. Penilaian kualiti air bawah tanah berdasarkan telaga persampelan yang dipilih secara rawak, akan menyebabkan berlebihan atau kekurangan maklumat. Maka, rangkaian telaga pemantauan harus dioptimakan supaya cekap maklumat dan kos berdasarkan data kualiti air bawah tanah sedia ada dan kerentanan akuifer. Model DRASTIC diaplikasikan sebagai model kerentanan berdasarkan kepada parameter fizikal alam sekitar untuk menilai zon potensi risiko pencemaran akuifer, menunjukkan lebih daripada 88% kawasan kajian diklasifikasikan sebagai berisiko rendah ke sederhana. Pendekatan baru dicadangkan untuk mereka semula jaringan telaga pemonitoran menggunakan algorithma optimisasi berdasarkan kerentanan akuifer kepada pencemaran, anggaran ralat telaga pemonitoran, jarak terdekat diantara telaga, dan sumber pencemaran di kawasan kajian. aplikasi anggaran ralat menunjukkan 100 dan 74 telaga pemonitoran adalah senario sesuai untuk memantau pencemaran semulajadi dan buatan manusia. Kombinasi daripada senario terpilih dalam GIS menunjukkan kapasiti mengenalpasti dalam sekitar 86% boleh didapati daripada 114 telaga pemonitoran daripada 154 telaga asal.

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I certify that a Thesis Examination Committee has met on 5 March 2015 to conduct the final examination of Tahoora Sheikhy Narany on her thesis entitled "Groundwater Quality Assessment and Optimization of Monitored Wells using Multivariate Geostatistical Techniques in Amol-Babol Plain, Iran" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the Doctor of Philosophy.

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LIST OF ABBREVIATIONS

A	Aquifer
ACF	Anthropogenic Contaminant Factor
ANOVA	Analysis of Variance
As	Arsenic
B	Boron
Be	Beryllium
BLUE	Best Linear Unbiased Estimator
BOD	Biochemical Oxygen Demand
BOD5	5-days Biochemical Oxygen Demand
C	Hydraulic Conductivity
Ca	Calcium
CA	Cluster Analysis
Cd	Cadmium
Cl	Chloride
Co	Cobalt
CO_3	Carbonate
COD	Chemical Oxygen Demand
Cr	Chromium
Cu	Cupper
D	Depth to Water
DEM	Digital Elevation Model
DO	Dissolved Solid
DWQI	Drinking Water Quality Index
EC	Electrical Conductivity
EPA	Environmental Protection Agency
F	Fluoride
FA	Factor Analysis
Fe	Iron
GIS	Geographic Information System
HACA	Hierarchical Agglomerated Cluster Analysis
HCO_3	Bicarbonate
HSD	Honestly Significant Different
I	Impact of Vadose Zone
IDW	Inverse Distance Weighting
IK	Indicator Kriging
IWQ	Irrigation Water Quality
K	Potassium
KMO	Kaiser Meyer Olkin
KRMSE	Kriged Reduced Mean Squared Error
K-S	Kolmogorov-Smirnov
Li	Lithium
LSD	Least Significant Difference
ME	Mean Error
MCM	Million Cubic Meter
Meq/L	Milliequivalents per Liter

Mg	Magnesium
MH	Magnesium Hazard
Mn	Manganese
Mo	Molybdenum
MRWA	Mazandaran Regional Water Authority
MSE	Mean Squared Error
Na%	Sodium Percent
Na	Sodium
NCF	Natural Contaminant Factor
NAN	Natural neighbors
NN	Nearest Neighbors
NO_2	Nitrite
NO_3	Nitrate
Nl	Nickel
Ok	Ordinary Kriging
Pb	Lead
PCA	Principal Component Analysis
PO_4	Phosphate
QA	Quality Assurance
QC	Quality Control
R	Net Recharge
RMSE	Root Mean Square Error
RSC	Residual Sodium Carbonate
S	Soil Media
SAR	Sodium Adsorption Ratio
Se	Selenium
SD	Standard Deviation
SO_4	Sulphate
SSP	Soluble Sodium Percentage
T	Topography
TDS	Total Dissolved Solid
TIN	Triangulation
Zn	Zinc

CHAPTER 1

INTRODUCTION

Groundwater has intrinsic valuable properties such as availability of reliable water resource compared with surface water, and compromising these properties has implication to human health (Aiuppa et al., 2003). Around 30% of the world's freshwater is stored as groundwater, which constitutes about 97% of all freshwater for human consumption (Delleur, 2010). Although, groundwater is mostly considered as an alternative source to surface water for drinking, domestic, irrigation, and industry usages, however it is relatively more reliable in terms of supply in arid and semi-arid areas because of its large storage, wide spread occurrence and protection from evapotranspiration and good quality of the water (Oladeji, 2012). It is also a vital element of groundwater dependent ecosystems such as wetlands.

Groundwater is the main source of water supply for potable and irrigation usages in the Amol-Babol Plain, Iran, where more than 70% of population utilize groundwater for drinking and agricultural activities (Fakharian, 2010). Fakharian (2010) reported that 68130 shallow and deep wells supply the water in the study area, where more than 80% of the plain's area constitute of agricultural lands such as irrigated lands, dry farming, and orchards. The large expanse of agricultural land is used to provide rice, crops, and citrus for growing population. Over exploitation of groundwater not only decreases the groundwater level, but also decrease the quality (Hoang, 2008). Extensive agricultural activities enable fertilizers and pesticides to leach into the groundwater, especially in shallow wells, which increase recognition of the impact of agricultural activities on groundwater quality. Moreover, surface runoff and soil erosion increase due to change land use patterns from forest and bush land to agricultural lands can impose negative stress to groundwater quality in the study area (MAHAB, 2004).

Poor drinking water quality, high cost of water purification, human health problems, and loss of water supply are attributable to groundwater contamination. The understanding of the chemical, physical, and biological conditions of groundwater and identification of the risks related to the groundwater quality are essential in devising planning strategies for groundwater resources protection. Effective management to support the water needs of the environment and its citizens depends on regular and systematic monitoring of groundwater resource. This kind of understanding can be obtained by groundwater monitoring which involves the water sampling to detect changes in the groundwater condition (Mogheir et al., 2006).

Groundwater monitoring can be defined as the scientifically-designed continuing measurement and observation of the groundwater situation, which also includes evaluation and reporting procedures (Jousma et al., 2006) (Figure 1.1). Data requirement for development, management, and control of groundwater sources may involve major monitoring program. Monitoring program should be in balance with the budgets and capacity available. Groundwater monitoring is a complex, time consuming, costly process, and measurement of all parameters at every well is impossible. In Amol-Babol Plain, lack of primary water quality data, results in the selection of the initial groundwater quality monitoring network to be highly subjective. Groundwater monitoring network with many sampling wells is costly and provide redundant information. The uncertainty and error of estimation of groundwater quality may be increased by reducing the sampling points. Therefore, the application of advanced research techniques requires estimation errors and uncertainty minimization of the groundwater quality. Furthermore, existence of efficient groundwater quality monitoring network can reduce deficient or redundant information as well as be effective in terms of cost (Baalousha, 2010).

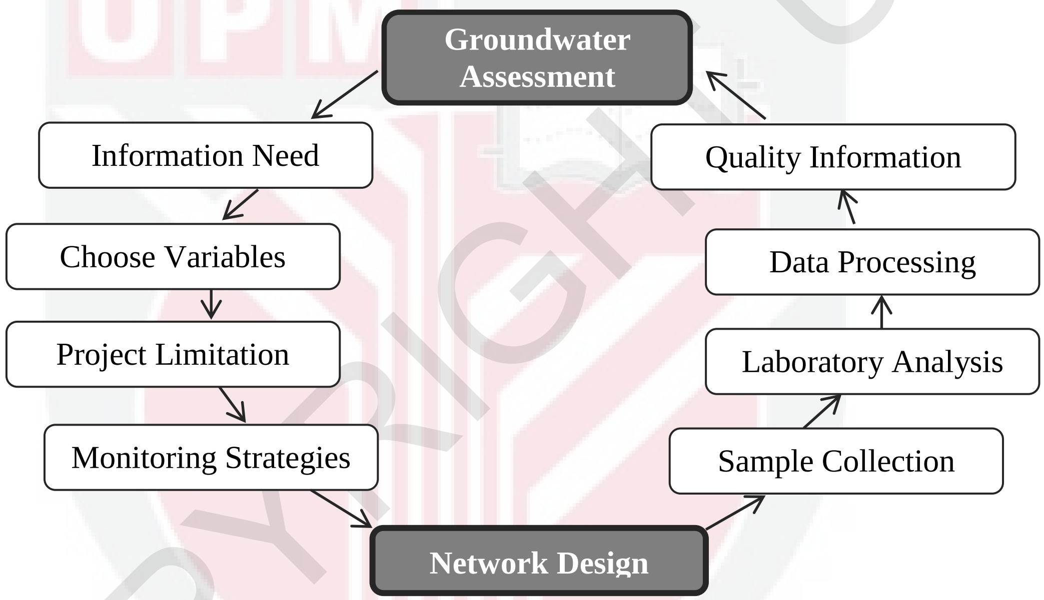

Figure 1.1 Water quality assessment and monitoring cycle
(Source: (Jousma et al., 2006))

Since the optimization of monitoring network is very complicated (Odom, 2003), the initial groundwater quality monitoring data, such as spatial distribution of quality parameters, aquifer hydrogeological information, and probable pollution sources play as a key role in assessing and redesigning status.

In Amol-Babol Plain previously studies restricted to drinking aspect of groundwater quality (MAHAB, 2004; Shahbazi & Esmaeili-Sari, 2009; Fakharian, 2010). Reliable picture of groundwater condition in different space and time can only be known by the integration of several techniques such as geostatistics, multivariate statistical analysis, classic geochemical methods, and vulnerability and risk assessment of aquifer to contamination (Wu et al., 2005; Baalousha, 2010; Chadalavada et al., 2011). Therefore, accurate assessment of initial monitoring networks requires optimizing groundwater monitoring network design in the study area.

Temporal and spatial assessments of groundwater quality with multiple parameters, which were collected from several monitoring stations at different monitoring times is an important step in characterizing groundwater condition. Therefore, a complex data matrix is frequently applied to evaluate water quality (Chapman, 1996). In groundwater monitoring, it is usually complicated to determine whether a variation in the concentration of measured parameters could be related to anthropogenic activities (mostly spatial) such as fertilizers, over pumping, industrial and residential sewages, and landfills or to natural changes (mostly temporal) such as seasonal variation, rainfall average, or tidal influence. Thus, parameters that are the most significant to describe such spatial and temporal variation and pollution sources without losing useful information had to be identified (Alberto et al., 2001). The combination of multivariate statistics and geostatistical techniques have been applied as unbiased methods in analysis of water quality data (Singh et al., 2004).

The application of multivariate statistical analysis such as cluster analysis (CA), principal component analysis (PCA), factor analysis (FA), and analysis of variance (ANOVA) in complex water quality data matrix is useful to reveal significant relationship between water chemistry parameters, better characterization the water quality situation, identification of possible factors that influence water quality and also for verifying spatial and temporal variation caused by natural and anthropogenic factors linked to seasonality (Helena et al., 2000; Singh et al., 2004).

Hydrogeochemical studies can identify the natural processes, such as seawater intrusion to fresh water, cation exchange, dissociation and precipitation of minerals, evaporation, and oxidation and reduction that influence groundwater quality. Hydrogeochemical processes are generally intercorrelated over space and time. The intercorrelations of hydrochemical variables are difficult to interprete and understand, especially if it involves a large number of variables. Several studies applied geochemical modeling and graphical methods for interpretation of water quality indices to evaluate the groundwater chemistry (Mondal et al., 2010; Reddy & Kumar, 2010; Wanda et al., 2011). Multivariate statistical techniques coupled with classic geochemical methods and geostatistical techniques had been successfully utilized to detect significant information from hydrogeochemical data in a complex system (Hoang, 2008; Nas & Berktay, 2010). This multidisciplinary approach could be useful in the identification of different physiochemical process in groundwater and to provide a unified method for spatial distribution of hydrochemistry parameters in thematic maps.

Natural and anthropogenic pollutants have threatened groundwater reliability and flexibility for irrigation purpose, where agriculture is a dominant economic activity. Quality of groundwater directly effects the soil's structure and crops production. Therefore, groundwater suitability for irrigation purpose needs to be assessed in order to improve water resource and land use planning. Although, traditional assessment of irrigation water quality based on the chemical indices such as sodium percentage (Na%), sodium adsorption ratio (SAR), and residual sodium carbonate (RSC) is simple (Adhikary et al., 2012; Ramesh. & Elango, 2012; Al-Taani, 2013), but it is not sufficient to provide an accurate picture of suitability of groundwater for irrigation purpose.

Irrigation water quality index (IWQ) was developed to assess irrigation water quality regarding to salinity hazard, infiltration hazard, specific ions hazard, trace elements hazard and miscellaneous effect (Simsek & Gunduz, 2007). Application of IWQ index without consideration of hydrogeological factors which influence to the potential of the aquifer for irrigation water abstraction, may adversely affect groundwater quality. Therefore, integration of the IWQ index and hydrogeological factors provide a powerful method for delineating groundwater suitability for irrigation purpose.

Spatial groundwater quality assessment is usually undertaken using geostatistical techniques within Geographical Information Systems (GIS) (Elçi & Polat, 2011). GIS were mostly applied for the management, visualization, and analysis of the monitored data by environmental specialists (Goovaerts et al., 2005; Kumar et al., 2007; Assaf & Saadeh, 2009; Nas & Berktay, 2010). In recent years, combination of GIS and geostatistical analysis are becoming an important tools to the optimal analysis of patterns in groundwater data (Adhikary, et al., 2010). Geostatistics is a spatial interpolation technique, which is used to estimate the concentration at un-sampled locations and predict spatial variation of groundwater properties (Johnston et al., 2001). Several scientists have applied kriging interpolation methods as the effective tools in consideration the spatial correlation between the measured points to estimate an unknown value (Dash et al., 2010). Kriging is distinguished from other interpolation methods such as Inverse Distance Weighting (IDW), due to application of the estimation of variance (Nas & Berktay, 2010), which can be used to measure the reliability of prediction, especially in optimization studies (Hoang, 2008).

Data collection from a finite number of sampling wells are necessary for identifying, understanding and describing the groundwater quality situation, which is critical in planning strategy for the protection of groundwater quality. Besides the significant role of collected samples from existing monitoring network, which reveal the source of contaminations and characterize the groundwater quality conditions, the aquifer vulnerability and risk to pollution should also be studied. In this context, the combination of field observation, and the sensitivity of groundwater to contamination determined using geostatistical analysis provide reliable method to optimize monitoring network wells. The sensitivity of groundwater to contamination is introduced by vulnerability, which is characterized by the hydrogeological and geological attributes of the aquifer (Farjad et al., 2012). DRASTIC is a standardized method for evaluating groundwater vulnerability to pollution, which was developed by the Environmental Protection Agency (EPA) (Aller et al., 1987). DRASTIC can be integrated with other information such as land use to evaluate the potential risk of contamination and identify areas which need special attention or protection (Osborn et al., 1998). DRASTIC is applied as one of the criteria in siting decisions to conduct groundwater monitoring. For example, denser sampling wells could be chosen in areas where aquifer vulnerability is higher and land use indicates a potential source of pollution. Generally, complex hydrogeological setting and limited information about contamination site are the primary sources of uncertainties in the site characterization (Chadalavada et al., 2011), which can be intensified by the uncertainties in number and location of network wells (Nabi et al., 2011). For this reason, the level of accuracy of the estimations should be considered in the monitoring wells using variance of error by geostatistics as another important criterion in network optimization (Ahmed, 2004; Chadalavada et al., 2011; Nabi et al., 2011). In view of this, adequate configuration of observation wells will accurately characterize the groundwater quality for a better management of the available sources under budgetary constraints.

1-1 Statement of Research Problem

Mazandaran is one of the wealthier provinces of Iran due to its high agricultural productivity and tourism activities, especially in the Amol and Babol Plain and in areas surrounding the Caspian Sea. Secondary data on population and climatic condition reveal that groundwater is the main sources of water supply for potable and irrigation purposes in Amol-Babol Plain. Since the last decades, about 10,000 wells have been constructed to supply water in the study area , where about 95% of the groundwater abstraction is attributed to agricultural activities (MAHAB, 2004; Fakharian, 2010). These abundant deep and shallow wells, which have been constructed by farmers for agriculture and domestic animal usages, exposed the groundwater under serious pressure. Based on the Mazandaran Regional Water Authority (MRWA) report, around 255.06 mcm of groundwater was drawn from 26,367 wells of the un-confined aquifer, out of which 139.81 MCM were used for domestic purpose, 111.24 MCM of groundwater were utilized for irrigation activities, and around 4 mcm were used for industrial purposes (Khairy & Janardhana, 2013).

The study area is located between recharge area (Alborz Mountain) in the southern side and discharge area (Caspian Sea) in the northern side thus groundwater quality could be influenced by several natural processes. Regional flow of groundwater is from the recharge zones in the southern side of the discharge area to the Caspian Sea in the northern area. The high flow rate had washed fossil saline water through sediment layers and prevented seawater intrusion into fresh aquifer water. In recent years, groundwater quality has been found to be degraded in the northern area, due to the influence of saline seawater and high evaporation of the fresh groundwater (Fakharian, 2010; Khairy & Janardhana, 2013). Over abstraction and utilization of freshwater in the plain will decrease the sea-ward flow and will lead to intrusion of seawater into coastal aquifer (MAHAB, 2004). Therefore, intrusion of saline water from Caspian Sea to freshwater could be reduced the groundwater quality for drinking and irrigation usages.

The population of Amol-Babal plain in 2007 was 1,080,840 inhabitants, where about 52.12% live in urban and around 47.82% rural areas. Urbanization changes the land use and transformation from rural to metropolitan pattern of organization, which has resulted in gradual deterioration of water quality (Mustapha & Aris, 2012). The most important urban area are Amol (population 343,747), Babol (population 261,733), and Ghaemshar (population 107,470), which don't have waste water collection and treatment systems (MAHAB, 2004). Waste water is discharged in absorbing wells in most part of the study area. Central and northern areas are the most densely populated which used groundwater for drinking purpose, especially in the rural area. Contamination of groundwater can result in poor drinking water quality which increases potential health problem, clean up coast, and alternative water supplies (Nas & Berktay, 2010).

Groundwater quality assessment is a significant issue for planning strategy for protection and control of groundwater quality, which is started by establishing groundwater monitoring network wells. The data collected from sampling wells are valuable for understanding and identifying the characterization of groundwater quality. Often, monitoring locations are arbitrarily located in single well or groups of wells, where pollution in the aquifer is first detected. However, they may not be ideally located for accurately identifying the release history of the pollution sources. Since, number and location of sampling wells play vital role on data obtained from groundwater. Designing monitoring wells in an optimal manner helps to delineate water quality with a minimum number of sampling wells at optimal location at a contaminated site (Chadalavada et al., 2011).

1-2 Rational of the Study

Groundwater quality has become a global concern due to its effect on human life and natural ecosystem, especially in arid and semi-arid region such as Amol-Babol Plain (Figure 1.2), which is under pressure with intensive agricultural activity and population growth rate. Protecting groundwater quality for human health and ecosystem is one of the serious issue in water management, which is highly depend on accurate view about groundwater quality conditions (Schmoll, 2006). Structured approach is required to identify significant factors that influenced groundwater quality, groundwater pollution sources, and vulnerable zones in the study area. Although, some researches were undertaken in the Mazandaran's groundwater (MAHAB, 2004; Shahbazi & Esmaeili-Sari, 2009; Fakharian, 2010), but, these studies mostly on the evaluation of the quality of groundwater as a drinking water based on WHO (2011a) and EPA (2011) standards.

Despite the several researches for groundwater monitoring network optimization, the majority of methods does not consider hydrology and hydrogeological characteristics of the aquifer, and mainly focus on only statistical aspects. Therefore, the integration of statistical, geostatistical, hydrogeological and hydrochemical methods are proposed as an adequate and reliable method for optimization groundwater quality monitoring network to improve groundwater monitoring strategies in the Amol-Babol Plain.

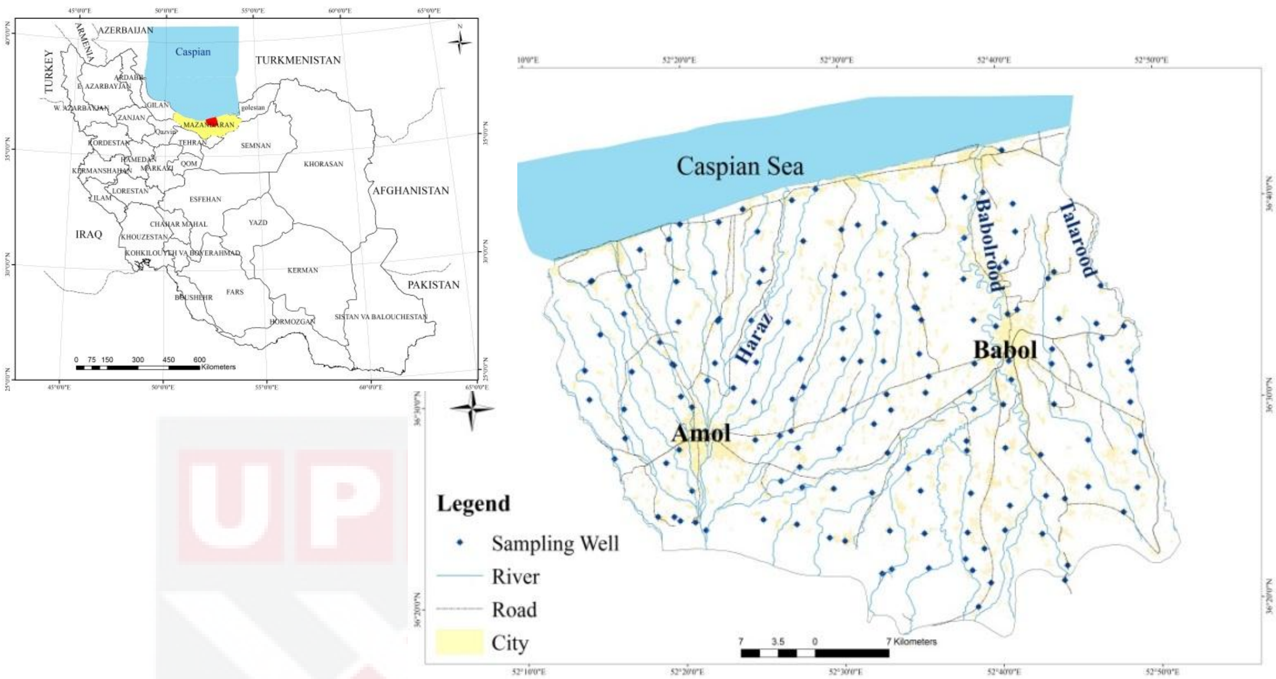

Figure 1.2 Schematic map of Iran showing the study area Amol–Babol Plain

1-3 Scope of the Study

Groundwater quality should be controlled on many sites to prevent migration of contaminants and keep groundwater safe for potable and agricultural usages. This study will be focused on assessment of groundwater quality for different usages, based on multivariate statistical analysis, geostatistical techniques, and hydrogeochemical investigation. Although, a typical monitoring program is needed to control groundwater quality, a typical monitoring program is very costly and time-consuming process. Therefore, a new approach will be suggested to optimize the groundwater monitoring network in Amol-Babol Plain, to provide the maximum information about the pollution sources in while employing the minimum number of sampling wells:

i. This study focus on the hydrochemistry of groundwater in the Amol-Babol Plain using integration of hydrochemical methods and geostatistical technique.

ii. Focuses on variation of groundwater quality, such as anions, cations, total and fecal coliforms, electrical conductivity (EC), dissolved oxygen (DO), total dissolved solid (TDS), and water temperature, and compared with international water quality standards for drinking and agriculture water.

iii. Applies the geostatistical interpolation techniques and multivariate statistical methods to identify significant parameters and possible pollution sources that influence groundwater quality in different time and space.

iv. Studies irrigation water quality index to identify suitable zones for agricultural activities, based on the salinity hazard, infiltration hazard, specific ions hazard, trace elements hazard, and miscellaneous effects using GIS-based index technique.

v. Concentrates to redesign information-cost effective groundwater quality monitoring wells, regarding to estimation of uncertainty in contamination concentration in the initial sampling wells and identification of risky zones based on the vulnerability and risk assessment and geostatistical estimation error approach in the study area.

1-4 Objectives of the Study

The main aim of this study is to assess and redesign the information-cost-effective groundwater monitoring network using geostatistical technique in Amol-Babol Plain, Iran. The specific objectives of this study are as follow:

i. To determine spatial and temporal variations of the groundwater quality and pollution sources.

ii. To characterize hydrogeochemical processes and spatial distribution on ionic ratios.

iii. To identify suitability zones of groundwater for irrigation purposes.

iv. To develop a new method to identify high potential risk zones based on anthropogenic contamination.

v. To redesign cost-effective groundwater quality monitoring network for the study area using geostatistical estimation error approach.

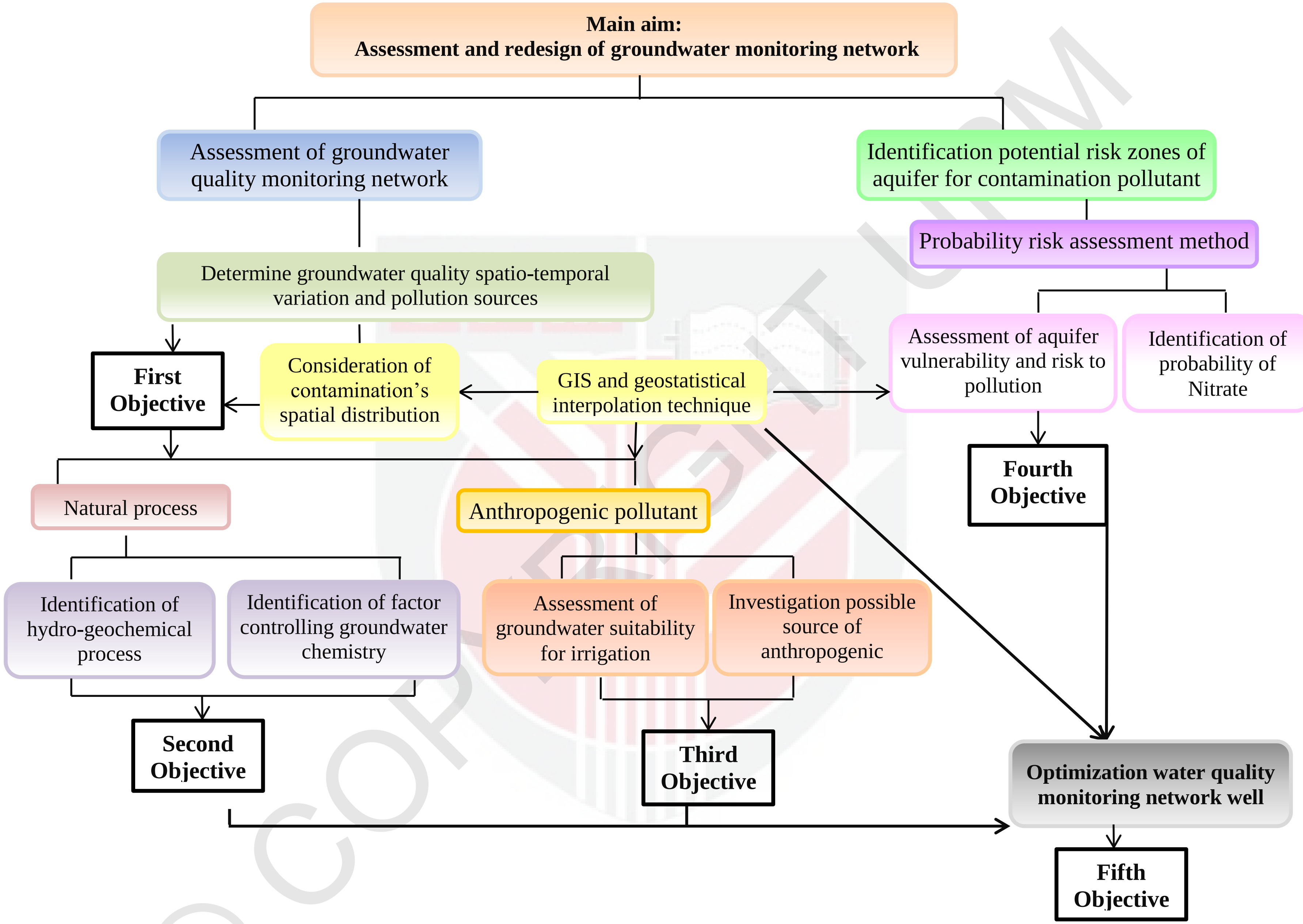

Figure 1.3 Conceptual framework of relationship between objectives and methodologies

1-5 Outline of Thesis

This thesis was organized into eight chapters. The results in chapters 3, 4, 5, and 7 had been published in ISI journals, and chapters 6 and 8 are still under review. These chapters have a specific introduction, methodology, result and discussion and conclusion.

Chapters 1, 2, and 3 introduce the motivation, back ground, and methodologies of the research in the study area.

Chapter 4 focuses on the first objective of the research, on spatial and temporal variations of groundwater quality parameters using multivariate statistical methods. Application of principal component analysis (PCA) and two-way ANOVA as a reliable approach revealed the significant factors influencing groundwater quality in the plain. Combination of multivariate analysis and geostatistical techniques demonstrate the possible source of contamination and the spatial structure of multivariate spatial data.

Chapter 5 focuses on the second objective of the research, which discuss the geochemical process, water chemistry type, and factors controlling the groundwater chemistry as natural factors influencing groundwater quality in the study area. Combinations of classic geochemical methods, statistical and geostatistical techniques, and PHREEQC software have been applied to characterize hydrogeochemical process of groundwater

Chapter 6 focuses on the first part of objective number three, which describes the suitability of groundwater for agricultural usage as a dominant economic activity in the Amol-Babol Plain. Application of irrigation water quality factors, geostatistical and statistical techniques, and geographic information system (GIS) revealed quality of groundwater for irrigation purpose.

Chapter 7 focuses on the second part of the third objective, which developed the irrigation water quality (IWQ) index in the Amol-Babol Plain and integrates with hydrogeological factors to assess suitable zones for agricultural activities in the study area.

Chapter 8 focuses on the fourth objective to evaluate the vulnerability and risk of aquifer to contamination using DRASTIC method and GIS. Application of indicator kriging provides powerful tool for identifying areas with probability of contaminants, specifically nitrate contamination in the study area. In this chapter, probability risk assessment had been proposed as new approach to identify areas with high potential to pollutant. DRASTIC method has been validated the efficiency of monitoring network.

Chapter 9 focuses on the fifth objective to develop new approach for designing an information-cost-effective groundwater monitoring network using geostatistics for extracting estimation error at all potential monitoring locations. To optimized monitoring network, extracted estimation error of significant parameters that influence the quality of groundwater, are combined with risk assessment map of aquifer. The efficiency of optimized monitoring network was examined using mass estimation error. The optimized monitoring network had been shown to provide accurate data for further water resource management under budgetary constraints.

Chapter 10 describes the conclusions of the finding of the studies and recommendations for future studies.

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LIST OF PUBLICATIONS

- **Sheikhy Narany, T.,** Ramli, M. F., Aris, A. Z., Sulaiman, W. N. A., & Fakharian, K. (2014). Assessment of the Potential Contamination Risk of Nitrate in Groundwater Using Indicator Kriging (in Amol–Babol Plain, Iran). In *From Sources to Solution* (pp. 273-277). Springer Singapore.

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- **Sheikhy Narany, T.,** Ramli, M. F., Aris, A. Z., Sulaiman, W. N. A., & Fakharian, K. A New GIS-Index integration approach to suitability assessment of groundwater for irrigation purposes. Environmental Science and Pollution Research (under review). Impact factor: 2.757

- **Sheikhy Narany, T.,** Ramli, M. F., Fakharian, K. Aris, A. Z., & Sulaiman, W. N. A., Information-cost-effective groundwater monitoring network design using geostatisical estimation approach. Stochastic Environmental Research and Risk Assessment. (under review). Impact factor: 2.673

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- **Sheikhy Narany, T.,** Ramli M.F., Aris A.Z., Esmaeil, W.N., Fakharian, K (2012). "Multivariate and Geostatistical Approaches in Assessment of Groundwater Quality for Drinking Purpose in Shallow Wells (Amol-Babol Plain, Iran)". *The International Conference on Water Resources (ICWR 2012), 6 November 2012, Langkawi, Malaysia.*

- **Sheikhy Narany, T.,** Ramli M.F., Aris A.Z., Esmaeil, W.N., Fakharian, K (2012). "Evaluation of arsenic contamination potential in groundwater using indicator kriging in Amol-Babol Plain, Iran". *40th International Association of Hydrogeologists Congress (IAH 2013)*.*15– 20 September 2013 Perth, Australia.*

- **Sheikhy Narany, T.,** Ramli M.F., Aris A.Z., Esmaeil, W.N., Fakharian, K (2012). "Assessment of the Potential Contamination Risk of Nitrate in Groundwater Using Indicator Kriging (in Amol–Babol Plain, Iran)" *International Conference of Environmental Forensics. 12-13November. Putrajaya. Malyasia.*

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