CHAPTER 1
INTRODUCTION

1.1 Background

"Water, Water, everywhere..."

Perhaps everyone heard this phrase. Water is present on Earth as surface water in the form of oceans, rivers, lakes, ponds, and ice, within the Earth as sub-surface water (as groundwater) and above the earth (atmosphere) in form of clouds, dust and air. Water is very essential part of the human life as well as other environment ecosystems.

Only 2.5% fresh water is available out of the total available global water, which is very less. Out of this 2.5% of fresh water, approx. 68.7% water has been found in ice sheets, ice caps and glaciers. 30.1% fresh water is available in the groundwater and approx. 1.2% fresh water is found as the surface water as shown in Figure 1.1 (Shiklomanov, 1993). If entrapped water in glaciers and ice caps is excluded, the largest reservoir of freshwater in the world will constitutes over 97% freshwater available on the earth from groundwater (Quevauviller, 2008). According to Quevauviller (2008), the total available drinking water on the Earth is 37 million km^3, and only 8 million km^3 of this available water is found in the groundwater resources.

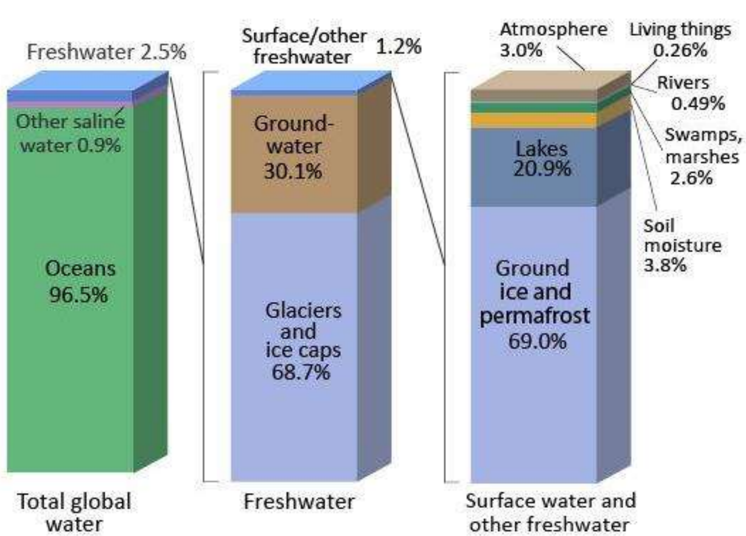

Figure 1.1 Schematic of the distribution of Earth's Water (Adopted from Shiklomanov, 1993)

Moreover, in recent years, groundwater became one of the essential natural resources in most part of countries in the world. Since, this groundwater source has the potential to supply freshwater, which offers essential benefits such as protection from pollutants that can contaminate this source, a lesser amount of seasonal water level fluctuations, and is uniformly spread over larger areas than the surface water, where it is often available in areas that are lack of surface water (Igor and Lorne, 2004). Therefore, freshwater supplied by the groundwater source will eventually become essential for domestic use, industry and especially agriculture. This urgency of freshwater is growing when depletion and contamination of the surface water sources is the issue (Siebert et al. 2010). Therefore, groundwater uses in the present and future is inevitably increasing. Therefore, sustainable and efficient management of the surface and sub-surface water resources becomes a significant challenge globally.

1.2 Groundwater Modeling

Groundwater flow is a specific case of water liquid stream in the porous media. It is a movement of water that occurs in the voids, available in the earth's bedrock. This movement of water depends on the characteristics of the medium, in which it occurs, and on the hydraulic head (water pressure). Groundwater moves slowly as compared to surface water and its movement is governed by the groundwater flow equation.

Researchers and scientists utilized many groundwater models and modeling methods for effective groundwater management. Groundwater modeling is a very difficult task due to sophisticated geotechnical and topographical properties, its infiltration distribution, boundary condition, recharge flow rate and the existence of many extraction wells in the system. The groundwater model is used for many purposes, as

1. To explore the performance of the groundwater system due to natural and artificial change in the system.

2. To study the main phase of groundwater related problem.

3. To use the model as groundwater management and development tool in decision making.

4. To comprehend the hydro-geological method characteristics and its relationship with groundwater.

The flow of groundwater in the aquifer system depends upon the three-dimensional configuration of the geological deposits. Darcy's law was the first approach for quantitative assessment of groundwater, which states that groundwater flow, strictly depends on the potential difference in groundwater head and conductivity of the medium through which groundwater flow takes place. When it is put together with an equation of continuity, a final governing partial differential equation of groundwater flow occurs. This governing equation is used to describe the flow in steady state and transient state conditions. The mathematical models can be used to obtain the solution of the governing equation and then calculate the distribution of hydraulic heads and the direction and rate of groundwater flow. These models use numerical or semi-analytic methods and allow us to get solutions in more than one dimension for complex boundary conditions and for heterogeneous and anisotropic aquifers.

For developing any groundwater flow model, there are two main approaches adopted by the researchers. One approach is Analytic Element Method (AEM) and second is the Grid Based Numerical method. Latter one Grid based numerical method consists of two different models (i) Finite Difference Method (FDM) and (ii) Finite Element Method (FEM). Usually, numerical method of modeling requires a lot of extensive data input. Moreover, the accuracy of these numerical models depends on the size of space, time discretization and its data input. The size of the discretization steps decides the error in solving the model equations. AEM model has benefit over other numerical model, as it does not require the discretization of internal model domain into cells or elements. The analytic elements in AEM are represented as line sources and sinks in rivers and drains or specified head and specified flow boundaries.

Wells are also mostly represented as points, and recharge and aquifer properties can be defined on polygons.

In the grid based numerical methods, pumping wells are approximately located and averaged over the cell of a grid, which becomes a cause of inaccurate location of wells. It becomes the cause of considerable error in solutions particularly when groundwater modeling for the large region where coarse grids are used. Additionally, the whole system should be solved and the head values at each cell should be computed in both FDM and FEM to get the groundwater head values even at a single cell, which in turns increases the computational time.

Selection of the numerical method depends upon objectives of the problem, available input data and hydro-geological form of the study region. The different solution methods have their own benefits and limitations and one can find appropriate method according to the requirements. There are so many groundwater modeling tools or software's are available such as MODFLOW (Modular three-dimensional finite-difference ground-water FLOW) developed by USGS (United States Geological Survey), FEMWATER (Finite Element Model of Water Flow), which is a three-dimensional simulating density-dependent flow and transport in variably saturated media, and AnAqSim (Analytic Aquifer simulator) is an analytic element software for simulating groundwater flow and it uses sub-domain models as described in Fitts (2010), which gives it strong capabilities with respect to heterogeneity and anisotropy.

1.3 Motivation: Groundwater Scenario in India

In India, Groundwater is a critical natural resource. Unscheduled and excess groundwater extraction along with inadequate groundwater recharge is causing key groundwater scarcity in various region of India. Due to excessive depletion of the groundwater, many problems such as land subsidence, shrinking of aquifers may arise. However, due to the overexploitation of the groundwater, a large number of aquifers have become unsustainable and are drying up very rapidly. A World Bank report says that if the current trend continues, in 20 years, about 60% of all the aquifers in India will be in critical condition. This will have serious implications for agricultural sustainability, long-term food security, livelihood, and economic development. It is estimated that more than a quarter of the country's crop will be at risk. These problems would cause serious issues in pumping costs, low stream base flow, changes in the groundwater flow patterns at the local or regional level, failure of established wells and risk to human life and infrastructure.

India is the only country utilizing largest amount of groundwater in the world. It exploits over a quarter of the global usage which is total approximately 230 cubic kilometres of groundwater per year. More than 60% of irrigated agriculture and 85% of drinking water supplies are dependent on the groundwater. Urban residents increasingly rely on the groundwater due to unreliable and inadequate municipal water supplies.

Groundwater serves as a crucial barrier against the unpredictability of monsoon rains. The value of the groundwater rises when there is a deficit of rainfall. For example, in 1963-66 rainfall decreased due to which India’s food production diminished by 20%. An almost analogous situation occurred in 1987-88, but by that time draught has a little influence on the food production due to the extensive use of groundwater.

As of April 2015, in terms of natural runoff flow in the river, the water resource potential or annual water availability in India is about 1,869 Billion Cubic Meter (BCM)/year (CWC Report, 2015). However, out of this total annual water availability, the usable water resources of the country have been estimated as 1,123 BCM/year. Water availability in the form of surface water and groundwater has been estimated as 690 BCM/year and 433 BCM/year, respectively as mentioned in Table 1.1. After excluding the estimated natural discharge approx. 35 BCM, the net annual groundwater accessibility for the entire country is expected to be 398 BCM. The uneven distribution of the water resources in the river network, and due to undulating topography of the country make it difficult to extract the total available water in the country.

Table 1.1 Statistics of water resources in India (Sources: Water and related Statistics, April 2015, Central Water Commission)

S No.	Parameter	Unit (Billion cubic meter/year)
01	Annual Water availability	1,869
02	Usable Water	1,123
03	Surface Water	690
04	Groundwater	433

The whole impact of rainfall to the country's annual groundwater resource is 68% and the share of other resources, such as seepage from canal, irrigation return flow, recharge from various water storage structures such as tanks, ponds and water conservation structures are taken together to be 32%. Due to expanding population in the country, the national per capita annual water accessibility has reduced from 1,816 to 1,544 cubic meters from 2001 to 2011 year (CWC Report, 2014). This is a drop of 15% groundwater resources in the country are evaluated at several scales.

1.4 Aim and Research Objectives (Groundwater Management)

Groundwater management includes the efficient and effective management of the groundwater resources at both the quantity and quality level (Gorelick et al. 1984). Quantity-based management of the groundwater resources is concerned with identifying the maximum groundwater extraction rate from pumping wells and the best location of new wells or reducing the installation and operation costs of pumping wells while considering the water demand.

This study is intended to evaluate the water resources (groundwater and surface water) in Varanasi and adjoining area, as well as to employ modern state-of-the-art MODFLOW, to assess the interaction between these two resources. MODFLOW is a computer code developed by USGS (United States Geological Survey) that solved the groundwater stream equation and it is considered the most accurate code in the groundwater modeling (Kumar, 2015). The main goals of the thesis are:

1. To develop a three-dimensional, multi-layered groundwater flow model for Varanasi and adjoining areas in transient state using MODFLOW code to simulate groundwater and surface water resources.
2. Comparison of the two approaches (FDM and AEM) used for the groundwater modeling by developing and conceptualizing the model for the study area.
3. Study the impact of the river stage on groundwater head in the study area. In addition, investigate the consequence of overexploitation of groundwater on the aquifer by formulating scenarios.
4. Identify the locations where river-aquifer interactions phenomenon takes place and quantification of the flux exchange between the River and Aquifer.
5. Prepare a management plan for groundwater in the study area to confirm the provision of scheduling of wells discharge rates, well locations, and impacts on groundwater aquifer system.

1.5 Organization of the Thesis

The thesis is divided into the following seven chapters.

- Chapter 01 contain introduction and significant information about the groundwater, its issues in India and overall the world. Objectives and scope of the proposed study are illustrated in Chapter 01.
- Comprehensive literature reviews on the past studies done by various researchers and scientists, which are related to the current study, are presented in the Chapter 02. The chapter discusses the studies, which were conceptualized by MODFLOW code, but at

the same time also discusses the other researches, which were carried out using different codes, developed for the groundwater flow analysis.

- Chapter 03 will explain the physiography and topography of the study area along with hydrogeology parameters. Chapter discusses about the characteristics of the groundwater aquifer, which are mainly affected the groundwater movement. Chapter also includes the river network in the study area.
- Chapter 04 illustrates the basic groundwater flow equation governing the groundwater flow movement. In this chapter, calculation of recharge rate and effect of discharge discussed along with groundwater-surface water (river) interaction. The boundary conditions and criteria required to calibrate and validate the groundwater flow model are also explained.
- Chapter 05 discusses the conceptualization of the groundwater model for the study area by using MODFLOW program. Applicability of the boundary conditions, calibration, and validation of the model has been described in the chapter.
- Chapter 06 discusses the interpretation of the results and explains the MODFLOW analysis considering the future water demand. Results of the river-aquifer interactions are also discussed in this chapter.
- Chapter 07 presents the conclusion of the study along with the limitations of the current work. Recommendations and future scope of the work is also listed in the chapter.