CHAPTER 2

LITERATURE REVIEW

2.1 GENERAL

Groundwater model is a management tool helps to understand the past and present hydrogeologic data and to predict the future hydrogeological condition towards sustainability of groundwater resources. Accuracy of the groundwater models depends on the quantity and quality of the field data used as an input parameters and boundary condition (Wang & Anderson 1982). Several studies have been carried out around the world on hydrogeological characterization, rainfall-runoff, surface water, groundwater flow and seawater intrusion modelling. This chapter discusses few research works carried out in rainfall-runoff, river flow and density dependent seawater intrusion model that are relevant to the present study.

2.2 SURFACE WATER MODELLING

Surface water modelling is a mathematical expression of natural phenomena that exchange rainfall volume into runoff volume. First comprehensive hydrologic computer model of Stanford Watershed Model was developed at Stanford University (Crawford & Linsley 1966). HEC-1 was developed by the Hydrological Engineering Centre, United States Army Corps of Engineers during late 1960. Presently, HEC-1 was renamed as HEC-HMS with the addition of user interface and spatial data input and analysis features. Rainfall-runoff models were developed based on conceptual representation of
the physical processes of the water flow lumped over the entire catchment area. Mostly used rainfall-runoff model are the Sacramento model (Burnash 1995), the United States Department of Agriculture (USDA) Curve Number (CN) method (SCS 1972, 1985), the Tank model (Sugawara 1995), the HBV model (Bergstrom 1995), and the MIKE 11/ NAM model (Nielsen & Hansen 1973, Havnø et al 1995).

2.2.1 Global Perspective

Anderson et al (2002) used HEC-HMS with an atmospheric model for prediction of watershed runoff in Sierra Nevada Mountains of California, USA. Shamsudin & Hashim (2002) estimated the rainfall runoff discharges of Sungai Layang watershed using MIKE11-NAM model. The satisfactory and reliable results were obtained with their Efficiency Index and Root Mean Square Error method. Zhan & Huang (2004) applied ArcCN - runoff tool (an extension of ESRI’s ArcGIS software) to determine the Curve Number and to calculate runoff or infiltration from a rainfall event for a watershed in Lyon County and Osage County, USA. Waichler & Wigmosta (2004) analyzed ephemeral stream flows by three models, namely Double Triangle Hydrograph, Composite Hydrograph and Channel infiltration model. The Composite hydrograph model is slightly preferable than the Double Triangle Hydrograph model for quantifying base flow.

Kafle et al (2004) used hydrologic model HEC-HMS in GIS environment to model basin scale rainfall-runoff modeling on the Bagmati basin in Nepal. Combination of GIS extension with HEC-GEOHMS is used to convert the precipitation excess to overland flow and channel runoff. The curve numbers are assigned based on the soil type and land use. McCuen et al (2006) used Nash–Sutcliffe efficiency index (Ef) for assessing the goodness of fit of hydrologic models. Chen et al (2008) used SCS-CN method and Green-Ampt method to simulate hydrologic responses in the Meilin watershed. Green-Ampt method obtained better results, especially on the simulation of peak stream flow as compared to those with the SCS curve number method.

Giang & Phuong (2010) used auto-calibration and trial-and-error method to calibrate and verify the MIKE 11-NAM model parameters. Auto-calibration is executed to locate the optima sets of parameters for individual storm event by using the shuffled complex evolution algorithm. This study
shows the auto-calibration is much easier and quick to find the best overall parameters than the traditional trial-and-error method. Doulgeris et al (2011) estimated the mean daily discharge by using MIKE 11-NAM model.

Amir et al (2013) used MIKE 11-NAM modelling system for large scale hydrological model in Fitzroy Basin, Australia. The model simulates the rainfall runoff processes for the three different interrelated storages, such as surface storage, root zone storage and groundwater storage. Hafezparast et al (2013) used MIKE 11-NAM lumped model to simulate the peak discharge and monthly flow at the catchment basin with limited daily and monthly discharge data. Hence, MIKE 11-NAM is a useful tool in water management models on the large scale modeling with middle and long term simulation periods. Lafdani et al (2013) simulated the runoff by using MIKE 11-NAM model. The result indicated that the efficiency of the NAM model was much more dependent on the quantity and quality of the data input model.

2.2.2 National Perspective

In India, Kumbhare & Rastogi (1984) tested the Nash (1958) conceptual model and found that runoff was generated in good agreement with actual runoff hydrograph. Pathak et al (1984) developed a model to predict runoff volume from small watershed to simulate daily monthly and annual runoff volume quite accurately. Kumar & Rastogi (1989) developed a mathematical model of the instantaneous unit hydrograph based on time area histogram for a small watershed at Pantnagar. Jain & Ramastry (1990) simulated the rainfall-runoff response in a part of Hemavati river basin by using the HEC-1 model. Kottegoda et al (2000) used statistical daily stream flow generator with simulated rainfall input when losses were obtained from an equivalent curve number related to the total rainfall event.
Srinivasulu & Jain (2006) compared various training methods of Multi-Layer Perception (MLP) type of Artificial Neural Networks (ANN’s) for modelling the rainfall–runoff process. Mishra et al (2007) used SCS-CN method for computing the direct runoff from long duration rains for five Indian watersheds. They derived curve numbers from long-term daily rainfall-runoff data and Antecedent Moisture Condition (AMC) related with antecedent duration. Patil et al (2008) estimated the runoff using curve number techniques (ISRE-CN) and validated with recorded data of Banha catchment in Damodar valley, Jharkhand, India.

Anuthaman (2009) used HEC-HMS and HEC-RAS which are freely available software to study groundwater augmentation by flood mitigation in Chennai region. The river basins of Adayar, Coovum, Korttalaiyar and Arani were delineated using the HEC-Geo RAS and ARC VIEW software packages. The river flood flows and its attenuation were analyzed by using HEC - HMS software. These flow conditions were classified as channel flow and bank full flow condition. The flood flow is attenuated for use as recharge to groundwater. Galkate et al (2012) simulated the rainfall-runoff in Bina basin, India by using MIKE11-NAM model. This model simulates the hydrological response of the basin to the rainfall and predicting daily runoff with high degree of accuracy. The model was seen performing well to simulate the runoff in good agreement with the observed runoff in terms of timing, rate, volume and shape of hydrograph.

2.2.3 Summary

The rainfall-runoff process is a complex activity as it is influenced by a number of implicit and explicit factors such as rainfall distribution, evaporation, transpiration, abstraction, watershed topography and soil types. Because of its non-linear and multi-dimensional nature, rainfall-runoff convert modeling is extremely complicated (Lipi wattanakarn et al 2004a).
The hydrological Model of NAM is an integrated and conceptual model of rainfall-runoff which is able to simulate surface flow, subsurface, groundwater recharge and base flow (DHI 1999). Hence, the present study was used MIKE 11 NAM model for the simulation of rainfall-runoff from the catchment.

2.3 GROUNDWATER FLOW MODELLING

Groundwater model is a simplified version of the real aquifer system that approximately simulates input-output stresses and responses relation to aquifer system (Thangarajan 2007). Groundwater models are the mathematical and digital tools used to study and analyze present aquifer condition and predict future behavior of the aquifer system on local regional scale, under varying geological environment. The models act an important role in the management and predictive measures on groundwater resources (Zhou & Li 2011). These models resolve the basic partial differential equations that manage the flow through porous medium and solute transport through unsaturated and saturated porous medium. Groundwater flow models have been used (Zhou & Li 2011): (1) as interpretative tool for investigating groundwater system dynamics and understanding the flow patterns, (2) as simulation tool for analyzing responses of the groundwater system to stresses, (3) as assessment tool for evaluating recharge, discharge, aquifer storage processes, and for quantifying sustainable yield, (4) as predictive tool for predicting future conditions or impacts of human activities, (5) as supporting tool for planning field data collection and designing practical solutions, (6) as screening tool for evaluating groundwater development scenarios, (7) as management tool for assessing alternative polices, and (8) as visualization tool for communicating key messages to public and decision-makers.
2.3.1 Simple Model

2.3.1.1 Global perspective

Groundwater hydrology began in the year 1935 by C.V Theis, suggested the flow of groundwater was analogous to the flow of heat in a solid (Theis 1935). Jacob (1940) derived a groundwater flow equation with the form of the heat flow equation that confirmed the Theis analogy. During 1940's, most of the well hydraulics problems were solved by classical analytical methods. In the beginning, hydrogeologists were used classical methods to estimate aquifer properties such as hydraulic conductivity and storativity. By 1950, a few investigators recognized that hydrogeologists needed a tool to concentrate on the larger issue of how an entire aquifer system would respond to hydrological stress (recharge and/or pumping). Bennett & Skibitski invented USGS electric analog computer model to solve various pumping and recharge conditions on entire aquifer system. The groundwater flow equation in electric analog computer model was described by equivalent electric analog i.e., voltage in an electrical analog is equivalent to temperature in heat flow and hydraulic head in groundwater. Electric analyzer was created to solve flow-net problem with a varying distribution of permeability at the Carter Oil Laboratory in Oklahoma in the 1930's. The Carter Analyzer used a finite-difference approximation of the equation of steady flow over the domain of interest, it had variable precision resistors that represented permeability. The analog computer model is first introduced idea of representing the aquifer as a finite-difference grid.

In analog computer model, all the components were fixed over a pegboard to represent model domain. Resistors are representing transmissivity and capacitors are representing storativity of the aquifer parameters. This was an important factor in both visualizing and selling models of aquifer systems. The USGS established an analog model laboratory in Phoenix where it was
routinely creating analog models of aquifers during 1960. Walton & Prickett (1963) studied scaling the electrical components to represent their hydrologic analogs. Toth (1963) first time used analytical solutions to investigate groundwater flow in hypothetical small drainage basins. Bredehoeft et al (1966) described an analog computer for a well that had a finite tube well and included the mass of the water in the well, it also includes a discussion of scaling analog computer components.

Due to the advancement of digital computer during late 1960's, the hydrogeologists focused on the creation of the digital groundwater model. Remson et al (1965) published application of numerical methods to solve the groundwater flow equation. Freeze & Witherspoon (1966, 1967, 1968) explained theoretical analysis of the regional groundwater flow in analytical and numerical solutions to the mathematical model. Pinder & Bredehoeft (1968) created a basic digital groundwater flow model. The USGS groundwater research group established numerical groundwater model for water supply problems in the realistic aquifer. This numerical groundwater model is used to simulate three dimensional groundwater flows in heterogeneous and anisotropic aquifer.

Freeze & Witherspoon (1968) also analyzed the effects of water table configuration, hydraulic conductivity on regional flow patterns and quantify basin yields. Later Freeze (1971) developed a transient saturated-unsaturated numerical model to investigate the relation between infiltration rates, water table rise and base flow hydrograph. Further, the model is used to predict maximum basin yield as a function of pumping pattern in recharge and discharge conditions. Bredehoeft & Pinder (1973) interested to simulate the steady state condition prior to pumping in order to calculate the hydraulic conductivity of the aquifer.
Digital model creates feasible solutions to the contaminant transport equation. Contaminant transport entails sharp interfaces associated with a plume of solutes, finite difference approximations rarely work because there is too much numerical dispersion. Bredehoeft & Pinder first published a transport model analysis during the year 1973. Konikow & Bredehoeft (1974) used transport code to simulate chemical quality changes in an alluvial aquifer. Computer-based numerical groundwater flow models were constructed to characterize flow systems and to simulate the effects of groundwater development on land use changes. The computer models of 3D finite difference (Trescott 1975) and the USGS MODLFOW (McDonald & Harbaugh 1988) are used in many purposes. In the year 1978 onwards the application of computer models on groundwater flow is started to simulate and process the large scale aquifer system with the Regional Aquifer System Analysis (RASA) program of the United States Geological Survey (Sun & Johnson 1994).

The groundwater models are the good management tool used to understand past and present condition of the aquifer system and used to predict the future reaction of the aquifer for any hydrogeological stresses like rainfall recharge and groundwater pumping (Anderson 1991). Fernando & Gerardo (1999) assessed the impact of urbanization on the groundwater resources of groundwater flow modelling and suggested an alternate place to relocate. Ayewen & Tilahun (2008) quantified and analyzed the safe yielding capacity of the aquifer by using three dimensional groundwater model. The simulated model results are used to forecast the groundwater flow pattern, the interaction of groundwater - surface water, and the effect of pumping on the well field under different scenarios.

Many researchers analyzed groundwater flow dynamics, flow pattern, the need for the improvement of groundwater level monitoring

Due to the limitation of finite difference method, it is difficult to consider complex aquifer with irregular boundaries on groundwater modelling. Advancement in computer technology, the complexity of the aquifer system and providing freedom for flow and solute transport in terms of inter nodal connection along all directions. In finite element technique, Galerkin’s method is most frequently used to solve groundwater problems. Galerkin’s method is based on the particular weighted residual principle which turns out to be equivalent to a variation principle. A weighted residual principle is expressed directly in terms of the governing partial differential equation without need to resort to a physical quantity (Wang & Anderson 1982). Rabbani (1994) started using finite element method for groundwater flow modelling. Finite element based software of FEFLOW is a powerful, comprehensive tool to simulate complex subsurface processes. FEFLOW has advanced computational methods of powerful mesh generator, automatic time stepping scheme, algebraic multigrid solver and parallelization (Diersch 1996).

Garcia-Aróstegui et al (1998) determined the important components of the water budget and identified river, aquifer and sea relationships by using finite element model. Nowadays, finite element based software of FEFLOW has been widely used to simulate multilayered complex aquifer system due to its modularization, visualization, interaction and diversified solving

2.3.1.2 National perspective

In India, 85% of rural drinking water met from dug and tube wells (The World Bank 2010) and 88% of groundwater exploited from the wells being used for irrigation purpose (IDFC Foundation 2013). Nearly 700 million Indian's living in villages entirely depends upon groundwater for their daily needs (Kulkarni et al 2015) and 48% of urban water demand is derived from groundwater (Centre for Science and Environment 2012). The rapid urbanization of India's town and cities has increased the fresh groundwater demand within urban agglomerations, also export water from adjoining villages (Janakrajan 2008). Groundwater from inland and coastal aquifers has been continued over pumping due to this demand. Hence, sustainable management and utilization of the groundwater resources are very essential. Several researchers have analyzed and predict the aquifer system for different pumping and recharge scenarios by using groundwater model.


Ahmed \& Umar (2009) evaluated the water balance in a poorly managed groundwater potential aquifer located in Yamuna-Krishna inter stream by visual MODFLOW Pro 4.1. Three scenarios were considered to predict aquifer responses under different abstraction conditions and the study suggested some recommendation to restore this aquifer. Senthilkumar \& Elango (2011) analyzed the effect of a subsurface barrier on groundwater flow in the Palar river basin, Tamil Nadu, India.

Ferrant et al (2014) created agro-hydrological model using downscaled Global Climate Model (GCM) data in order to evaluate climate change effects on local groundwater extraction. A small increase of precipitation might improve current groundwater depletion on average, despite the increased evaporation due to warming. However, projected climatic extremes create worse groundwater depletion shortages than for present climate. Local conditions may lead to opposing impacts on groundwater depletion increases and decreases (+/-20 mm/year), for a spatially homogeneous climate change forcing.

Sivakumar \& Elango (2010) studied salinisation processes and time taken to flush tsunami-induced salinisation with the help of finite element
solute transport modelling software of FEFLOW 5.2 version in Kalpakkam region, Tamil Nadu, India. Mondal et al (2010) simulated real field aquifer near Vadodara, India for a combination of flushing and pumping to demonstrate the effectiveness of the proposed multi-objective technique for achieving the optimal pumping policy by using FEM-NSGA II model.

Ramesh & Mahesha (2011) simulated the effect of interlinking of rivers on groundwater level variations by using two-dimensional Galerkin finite element model. The simulated results indicated an increase of groundwater level which was explained to the resource managers and decision makers by excellent visual demonstration of animation to understand the nature of relation between surface water and groundwater. Kulkarni & Rastogi (2012) assessed the best performance of the different groundwater models such as finite difference method (FDFLOW) with Galerkin finite element method (FEFLOW), solute transport based on Galerkin finite element method (FESOLUTE), random walk method (RWSOLUTE) and modified methods of characteristic (MMOCSOLUTE). The study results show the FEFLOW-MMOC SOLUTE model performed well. Elango et al (2012) estimated the impact of radiology on groundwater by using the finite element FEFLOW model in an around a proposed uranium tailings pond at Seripalli in Andhra Pradesh, India. Literatures presented one of the problems in coastal aquifer's of seawater intrusion discussing the detail in following section.

2.3.2 Density-Dependent Seawater Intrusion Model

Several researchers studied the seawater intrusion by using mathematical models. Salt concentration from the seawater has been continuously diluted with fresh water and high concentration of salt can affect the density of fresh water. Hence, solute transport model requires advection, dispersion equation with density effect. History of applying analytical and
numerical methods for density dependent seawater intrusion problem is discussed in the following section.

2.3.2.1 Global perspective

A French teacher, Joseph Ducommun is first described seawater intrusion by state freshwater balance of the coastal aquifer in 1828. Later in 1855, Braithn Waite demonstrated the salinity increase in the draw water well in London and Liverpool (Liu & Song 2010). Ghijsen (1889) from Holland and Herzberg (1901) from Germany respectively found G-H balance equation about the coastal aquifer. The G - H equation describes the position of an interface between fresh and saline groundwater as follows Dupuit assumption ie. fresh water head from water outlet is assumed by zero. Muskat (1937) & Hubbert (1940) altered the G - H equation to describe the seawater-freshwater interface more precisely. But, this equation is only suitable to the sudden change in the interface

During 1959, Glover assumed that seawater is static on the consideration of the flow and flux of fresh water take advantage of upper pressure connection from subject interface. Seawater - freshwater boundary equation is used to setup complex variable function in coastal aquifers. Glover (1959) studied the pattern of freshwater flow in a coastal aquifer. Henry (1959) established the solution to interface for sudden change, defined quantitative effect on the seawater intrusion due to advection scatter and changed density by using Cooper’s assumption. Henry produced a new method using the advection scatter model to replace the sudden change in the interface model and regard fresh water as the mixed fluid.

Volker (1974) utilized finite element technique to determine mean long term position of the seawater - freshwater interface under different recharge and pumping conditions. Pinder & Page (1976) considered the
seawater - freshwater as the two kinds of flow separated by the interface. This method is also used two dimensional seawater intrusion problem of vertical difference less vertical water head and the narrower mixed area. Andrews (1981) first studied two dimensional seawater intrusion by assuming that seawater is static due to Dupit assumption. They used the finite difference method to predict the groundwater head and applied to the regional water resources management model.

The three-dimensional advection scatter model is being applied to the practical seawater intrusion project. Till 1980's, the behavior of density dependent groundwater flow has been investigated by means of analogue models (e.g. Hele Shaw model for multiple fluid flow to study wastewater injection into a fresh saline groundwater system) and analytical solutions. Bear et al (1985) described a method for determining the motion of the seawater interface in an unconfined coastal aquifer during a specified time period in response to changing hydrologic conditions.

Rapid developments of computer technologies, the mathematical models are solved by numerical methods. Nowadays large number of computer models is available to simulate seawater - freshwater interface in the aquifer system. The mathematical explanation of the solute transport models of seawater intrusion found by a different scientist such as Galeati et al (1992), Diersch (1996), Person et al (1996), Holzbecher (1998), Ingebritsen & Sanford (1998), Bear et al (1999) and Diersch & Kolditz (2002).

Some of the benchmark problems were used for model testing and comparing the results of another model, with reality, model verification of problems for which analytical solutions exist (Essink 2003). Benchmark problems are namely Henry's problem, hydrocoin problem, elder problem, rotating immiscible interface and salt pool problem. In general, benchmark problems are used to verify the code. Henry is the one first developed
analytical solution for density-dependent groundwater flow with hydrodynamic dispersion. Henry benchmark problem is generally used to compare new numerical techniques and verify other models. Hydrocoin problem is the steady state flow and transport problem which is developed to characterize high level nuclear waste disposal site in Germany. Elder problem is a free convection problem in a rectangular homogeneous porous medium and it is more sensitive to the model discretisation and convergence. The benchmark problem of saltpool requires a stable layering of saltwater below freshwater (Johannsen et al 2002). Another benchmark problem of rotating immiscible interface problem comprises of the movement of three immiscible fluids of different densities (Bakker et al 2003). This benchmark problem is proposed particularly for the verification of the density-dependent flow part of groundwater code.


Larabi et al (1997) assessed the problem of the seawater intrusion in the unconfined and confined aquifer through test problems using finite
element equations. The results of test problem show more accurate when compared with the analytical solutions. Benson et al (1998) compared the performance of the finite difference and finite element methods. Finite-difference method used the Lagrangian based flow and transport code, it shows slow convergence to correct solution of Henry’s problems. In finite element method, an Eulerian code is used to understand the convergence of the model. The solution converges quickly and displayed the uniform velocity vector.

Ataie-Ashtiani et al (1999) evaluated the effects of tidal fluctuations of the seawater intrusion in an unconfined aquifer by using variable density groundwater model code of SUTRA. Tidal activity forces the seawater to intrude further inland and it also creates a thicker interface than occur without tidal effects. In general, the sloping beaches have more impact in the seawater intrusion compared to the vertical face beach due to tidal activity. Because, there will be a less increase of the groundwater level occurred by tidal fluctuations at the vertical face. In the case of the sloping beach, sloping edge of beach allows seawater to moves easily to fresh water aquifer at the high tide period and then infiltrate vertically through the top of the aquifer.

Cheng & Chen (2001) developed a three dimensional variable density flow and transport model of coupled Eulerian - Lagrangian method to simulate the seawater intrusion for various pumping and tidal effect in the Jahe river basin, China. The results show that excessive groundwater pumping and improper arrangement of pumping wells causes more seawater intrusion than tidal variation. Bell et al (2001) determined the extent of seawater intrusion by mapping Melaleuca dieback using Airborne Polarimetric Synthetic Aperture Radar (AirSAR) fused with Thematic Mapper (TM). The changes in the distribution of Melaleuca are an excellent bio-indicator of the
state and history of saltwater intrusion. Extrapolation of Melaleuca dieback to infer the spatial extent of saltwater intrusion. The combined data set of optical and AirSAR in resolving the overlap of land cover types.

Milnes & Renard (2002) assessed the impact of irrigation return flow in seawater intrusion in the coastal aquifer by three-dimensional finite element based computer code of FEFLOW. The salinization mechanisms underlying seawater intrusion and mass return flow from irrigation are entirely different, but they are linked within seawater intrusion settings by the fact that the water quality degradation within the pumping wells caused by an advancing sea front enhances salinization by irrigation. On the other hand, intensive agricultural activity (e.g. over exploitation) leads to enhanced the seawater intrusion by lowering of the water table.

Dim & Chikita (2004) developed the analytical and numerical models to determine the shape and position of the interface between the landward seawater intrusion and the subsurface freshwater outflow around the coastal area by using Heat and Transport code. The result indicates that the impact of sea level rise is very less compared to over exploitation of groundwater in the problem of seawater intrusion.

Shoemaker (2004) studied the sensitivity analysis in the density-dependent ground water flow to understand the calibration of seawater intrusion problem. The approach is used to represent (1) the relative importance of various flow and transport parameters for reproducing hydraulic head, salinity, and flow observations, (2) observation locations and observation types likely to be most effective for estimating dispersivity parameter, (3) parameters that may not be uniquely estimated with a given set of observations because of extreme parameter correlation, and (4) the types of observations that may reduce correlation between parameter values and encourage unique estimates.
Werner & Gallagher (2006) developed the seawater intrusion model using MODHMS code to explore regional scale processes and to aid assessment of management strategies for the system. Hydrodynamic calibration preceded the construction of the seawater intrusion model was efficient, although some errors were introduced by the vertical discretisation approach of layer subdivision. Tber & Talibi (2007) used inverse problem to determine the hydraulic conductivity in the seawater intrusion problem by using finite element method of sharp interface. The problem is formulated as a minimization where the cost function calculates the squared error between the observed and computed conductivity values.

Kopsiaftis & Mantoglou (2008) estimated the hydraulic conductivity in a heterogeneous unconfined coastal aquifer by using PEST algorithm and FEFLOW. A 3D variable density model is compared to a 3D single flow model and sharp interface model. The results indicate that the transition zone in this aquifer is expected to be relatively narrow and piezometric head of the aquifer depends mainly on head boundary conditions.

Alberti et al (2009) conducted a seawater intrusion study in order to understand the position of the freshwater-seawater interface, as influenced by the hydrogeologic structure and the presence of industrial activities by using finite element based computer package of FEFLOW at an oil-refinery site located on the coast in the lower Esino Valley, Italy. In the seawater intrusion model, the distribution of chloride is dependent on the initial chloride distribution. It also change based on the rate of groundwater abstraction and available surface water level in the rivers and ponds.

Hu & Xu (2010) studied the response of the tidal influenced river system in the coastal aquifer system by using three-dimensional finite-element flow and solute transport model of FEFLOW. The results indicated that, there was a considerable amount of changes occurred in the solute due to
The river water level has reduced the extent of the saltwater intrusion. Praveena et al (2011) assess the present condition of the seawater intrusion in Manukan Island and predict the future condition of seawater front by different recharge and pumping scenarios by using SEAWAT-2000. Abiola & Agbede (2012) studied two dimensional dispersion problems in an over exploited multi-layered aquifer by the finite element method. Cobaner et al (2012) simulated seawater intrusion mechanism of the Goksu Deltaic Plain along the Mediterranean coast of Turkey by three-dimensional variable density groundwater flow model of SEAWAT. The simulation results show that the Goksu Deltaic Plain aquifer is especially sensitive to the increase in groundwater extraction. The different groundwater models helps to establish management policies in groundwater pumping and crop patterns needs to chosen by farmers during less rainfall period.

Rusi & Tatangelo (2010) carried out hydrogeological investigations and numerical analysis on Sangro and Vomano rivers alluvial plains, central Italy by using an integrated approach of ESRI ArcGIS platform, finite-difference MODFLOW and density-dependent finite element FEFLOW numerical codes. These models have been used to investigate some major issues, concerning optimization of well fields, pumping regimes as well as the establishment of wellhead protection areas. Liu & Mao (2011) studied the impact of boundary conditions on the seawater intrusion by using finite element computer code of FEFLOW. The extent of seawater intrusion is determined by both horizontal water head gradient along the bottom of the aquifer and vertical water head gradient along the beach. The study found that the vertical gradient has greater impact on seawater intrusion than the horizontal gradient. Lu & Yang (2011) simulated the extent of seawater intrusion for different pumping and tidal scenarios by using FEFLOW.
Dokou & Karatzas (2012) measured the extent of seawater intrusion in a karstified coastal aquifer in Crete, Greece by FEFLOW and also the finite element model is compared to the more traditional sharp-interface approach. The karstified medium was modeled using a combination of the equivalent porous medium approach (for lower-order fractures) and a discrete fracture approach (for the main fractures/faults). The direction of the fractures, the rate of pumping and the density of fluid are the main driving factors for the movement seawater front. Gaaloul et al (2012) assessed the extent of groundwater contamination by marine salts using finite element method.

Werner et al (2012) identified the seawater intrusion vulnerability indicators using an existing analytical solution for the steady state position of a sharp seawater - freshwater interface. Interface characteristics of wedge toe location and seawater volume are used in quantifying seawater intrusion in both the confined and unconfined aquifers. The different factors increasing the vulnerability of seawater intrusion including: (1) sea level rise impacts are more extensive in aquifers with head-controlled rather than flux controlled inland boundaries, whereas the opposite is true for recharge change impacts, (2) sea level rise does not induce seawater intrusion in constant discharge confined aquifers, (3) vulnerability varies depending on the causal factor, and therefore vulnerability composites are needed that differentiate the vulnerability to such threats as sea level rise, climate change and changes in seaward groundwater discharge

Kafri et al (2013) simulated the flow pattern and the seawater intrusion all the way from the sea to the endorheic base level using FEFLOW. When the concentration of the water in base level is brine through evaporation, the high concentration of salinity water starts to flow below the seawater in the opposite direction towards the sea. The results of numerical
simulations support the feasibility of the seawater intrusion into deep endorheic saline base levels below sea level.

Mazi et al (2013) investigated the responses of the seawater intrusion in the unconfined sloping coastal aquifers to climate driven sea level rise by the analytical model. The results show high nonlinearity in responses implying important thresholds or tipping points beyond which the responses of the seawater intrusion to sea level rise shift abruptly from a stable state of mild change responses to a new stable state of large responses to small changes that can rapidly lead to full seawater intrusion into a coastal aquifer. The three types of tipping points are identified: (a) spatial, (b) temporal, and (c) managerial.

2.3.2.2 National perspective

India has 7,517 km length of shoreline. Water resources in coastal areas are more importance since fresh water in the coastal aquifers is liable to experience irreversible effects because of over exploitation of groundwater resources and sea level rise. Groundwater pumping in abundance of safe yields and decreased to groundwater recharge because of rapidly changing land use pattern along the coasts has expanded the rates of seawater intrusion into coastal aquifers. MINOS algorithm uses the projected augmented Lagrangian method of nonlinear programming (Murtagh & Saunders 1993) to solve the finite difference approximated governing equations used in the seawater intrusion. The main advantage of this method is sequential, iterative solutions of the flow and transport equations are not necessary. Das & Dutta (1995) developed a number of nonlinear multi-objective management models to manage the coastal aquifers under steady and transient conditions. The nonlinear finite difference form of density-dependent miscible flow and solute transport model for the seawater intrusion in the coastal aquifer is embedded within the constraints of the model. The results indicate that the potential
applicability of planned pumping strategy is a tool for controlling and managing the coastal aquifers prone to seawater intrusion.

Das & Datta (2001) carried out the density-dependent miscible flow and transport modeling approach for simulation of the seawater intrusion in the coastal aquifers. Mahesha (2001) presented an overview of major theoretical and field investigations regarding the techniques to control of seawater intrusion. Bobba (2002) evaluated the effect of human activities and sea level changes in the spatial and temporal behavior of the coupled mechanism of seawater and freshwater flow through density-driven software of SUTRA in the Godavari Delta of India. Mahesha & Babu (2002) studied the effect of subsurface barrier on the motion of the seawater - freshwater interface in coastal aquifers with the Galerkin finite element model for sudden freshwater drawdown conditions. The variations in the interface profile are compared to no barrier condition. Width and hydraulic conductivity plays a decisive role in delaying the interface response for any drawdown situations. The initial length of the seawater intrusion is main factor to construct barriers at the suitable location.

Rao et al (2004) solved the multi-objective management problem of the seawater intrusion by a coupled simulation – optimization approach. A density-dependent groundwater flow and transport model is used to simulate the dynamics of seawater intrusion using SEAWAT software. The idea of replacing the SEAWAT model with a trained artificial neural network (ANN) to manage the computational burden within practical time frames on a desktop computer is explored.


Saldanha et al (2009) simulated the seawater intrusion by considering different pumping scenarios in the Pavanje river sub basin, India by using FEFLOW. Seawater intrusion is predicted at some specific locations due to low water table condition during the summer. The water budget estimation shows that there is a significant groundwater outflow from the area during June to November. Hence, it is necessary to carry out investigations to arrest this outflow which may be utilized during the summer season.


Kale et al (2012) studied the seawater intrusion with the help of the Hele – Shaw model. Soni & Pujari (2012) examined some point to ponder on seawater intrusion studies in coastal aquifers. Based on interdisciplinary approaches, accuracy in evaluation plan and procedure can be achieved. Sophiya & Syed (2013) assessed the vulnerability to seawater intrusion in the Ramanathapuram district of Eastern India by using GALDIT method. The vulnerability of the study area was also analyzed for the year 2050 by considering an average global mean sea level rise of 3.1 mm/ year.
Lathashri & Mahesha (2015) conceptually simulated groundwater flow and transport for a coastal stretch in Karnataka state, India by using SEAWAT -2000. A single layered model is developed due to the lack of hydro-geological data of the deeper aquifer. The accuracy of the model is evaluated by comparing observed groundwater level and chloride values were compared with simulated values on seasonal basis.

2.3.3 Summary

Several researchers studied density-dependent seawater intrusion by using finite difference and finite element approach. There was no study carried out with the integrated modelling of rainfall-runoff, infiltration and density-dependent seawater intrusion. Hence, the present study was used the integrated approach in the density-dependent seawater intrusion model.

2.4 INTEGRATED SURFACE AND GROUNDWATER MODEL

Surface and subsurface flow systems are naturally combined that are frequently broken into separate sections for logical (e.g time scales) and technical (e.g. analytical and computational) reasons. An integrated surface and groundwater flow, one or more watersheds are simultaneously simulated the flow across the land surface, within saturated and unsaturated subsurface and within streams and lakes (Furman 2008). In general, surface water model includes a temporal portion where rainfall is the only source to supply water for surface and subsurface system. Amount of surface water infiltrates into the subsurface groundwater system depends on the rainfall rate and soil infiltration capacity (Markstrom et al 2008). The surface - groundwater systems follow different partial differential equations. Therefore, the boundary condition is used to represent the interactions between the systems. Few researches carried out by integrated surface water and groundwater approach is reviewed in the following section.
2.4.1 Global Perspective

Crebas et al (1984) describes a physically based hydrological approach to study the drainage and the interaction between open channel flow and groundwater. There are two types of exchange considered for the integrated surface and groundwater model. The first type is concerned with the influence of minor conduits which requires too much refinement on an individual basis, but complex makes an important contribution to the water budget of a region on an areal basis. The second type of exchange is direct seepage from or into the larger waterways in which the flow is significant. Vries (1995) reported coupling the mathematical expressions for groundwater drainage and stream flow enables development of a conjunctive model which relates the properties of a seasonally contracting stream network and groundwater level fluctuation.

Langevin et al (2005) simulated the surface water flow and transport code integrated with the SEAWAT variable density groundwater code. A sequentially coupled time lagged approach is implemented based on a variable-density form of Darcy’s law to couple surface and subsurface systems.

Kollet & Maxwell (2006) incorporated a new two dimensional overland flow simulated into the parallel three dimensional variably saturated subsurface flow code ParFlow for coupled model. This new overland flow simulator takes the form of an upper boundary condition and fully integrated without relying on the conductance concept. Another important advantage of this approach is an efficient parallelism integrated into ParFlow, which is exploited by the overland flow. The model is shown to reproduce an analytical solution for overland flow, replicates a laboratory experiment for surface–subsurface flow and compares favorably to other commonly used hydrologic models. The propagation of uncertainty due to subsurface
heterogeneity to the overland flow and demonstrate the usefulness of our approach.

He (2007) analyzed the application of a spatially Distributed Large Basin Runoff Model (DLRBM) in the Great Lakes Basin of the United States. Large scale combined hydrologic models are based on the mass continuity equations include land surface, soil zones and groundwater components.

Müller-Wohlfeil & Mielby (2008) assessed the interactions between surface water and groundwater for both under current and future conditions with respect to groundwater withdrawal. Smits & Hemker (2009) reported different computer program of Duflow and MicroFem for the coupling of surface water and groundwater. Duflow is a computer program used to simulate the one-dimensional modelling of surface water. MicroFem is a finite element model that simulates saturated groundwater flow. The regional coupled model is constructed for the consideration of surface water infiltration to the groundwater model. When comparing the individual surface water and groundwater models, coupled models have excess value in all conditions where ever the groundwater system connected to the surface water system.

Hughes et al (2010) estimated sustainable abstraction volumes in a semi-arid catchment and assessed uncertainties of model parameters by simple coupled surface and groundwater hydrological model. This model is able to simulate the interactions between surface - ground water and the effects of abstractions in a realistic manner. However, the values of the various simulated components of the ground water balance as well as the estimation of sustainable abstraction volumes are subject to a large degree of uncertainty.
Monninkhoff et al (2010) developed a coupled surface (MIKE 11) - groundwater (FEFLOW) model is used to simulate all the physical processes that are relevant to the interactions between the surface and groundwater system. The module of IfmMIKE11 is used to couple FEFLOW and MIKE11 and it has been extended for mass-transport processes. Monninkhoff & Hartnack (2011) developed a new IFM function in FEFLOW to represent the real exchange area between river and groundwater, which mainly depends on the river profile and water depth. The new IFM function represents the exchange area by node as well as a nodal transfer rate. This function can now be optionally used in IfmMIKE11.

Zampieri et al (2012) applied observational evidence and parameterization for improving the representation of river–groundwater interactions in the Community Land Model (CLM). CLM has the ability to reproduce the soil moisture and surface temperature spatial variability's that relate to the river distribution at regional scale. The CLM with new parameterization is used to evaluate impacts of the improved representation of river–groundwater interactions on the simulated water cycle parameters and surface energy budget at the regional scale.

Hassan et al (2014) applied an integrated modelling approach of GSFLOW to structural and hydrological complex hard rock systems. Monninkhoff et al (2014) analyzed the effect of groundwater influenced the flooding of a large abandoned mining area in eastern Germany using coupled surface - groundwater model. The flooding process was reproduced using the plug-in of IfmMIKE11, which couples the groundwater model of FEFLOW with the surface water model of MIKE11.

Schepper et al (2015) investigated the applicability of various tile drainage modeling concepts by comparing their results to a reference model. A series of simulations is performed to test the influence of flow boundary
conditions, the temporal resolution of precipitation data, conceptual representations of clay tills as well as a spatial discretization of the mesh. For larger scale models, the simulations suggest that a simplification of the geometry of the drainage network is a suitable option for avoiding highly discretized meshes. It greatly reduces the mesh complexity and simulation time and thus represents an alternative to a discrete representation of drains at the field scale, but specifying the hydraulic properties of the layer requires calibration against observed drain discharge.

2.4.2 National Perspective

In India, there is no considerable research carried out with integrated surface water-groundwater approach. Pahar & Dhar (2014) carried out a coupled model for dry and wet zone based on profile measurement. The model considered Saint Venant equations, Darcy’s law and Boussinesq equation. Ground water flow is simulated by using Darcy’s law and Boussinesq’s equation. Surface water model is simulated by Navier–Stokes equation of continuity and momentum. The mathematical model uses a finite difference method with upwinding scheme for the discretization of the governing equations and Newton-Rhapson method for solving the equations. A novel dry zone-wet zone theory is proposed for modeling the system.

2.4.3 Summary

As many researchers were carried out the integrated surface and groundwater modelling for different aquifer system, there was no study carried out with the long term data to assess possible measures to mitigate the seawater intrusion in the coastal aquifer system.
2.5 PREVIOUS MODELLING STUDIES IN A-K BASIN

UNDP/CMWSSB had (1965-69, 1975-78, 1982-85 Phase I) a series of studies carried out first in Arani - Korttalaiyar (A-K) river basin (CGWB 2007). During this period satellite image analysis, hydrology, hydrogeology, recharge studies, seawater intrusion, artificial recharge, socio-economic studies and water quality studies were undertaken. UNDP had a research of a Phase II study between 1986 and 1991 in the Korttalaiyar river basin alone (Piesold 2005). A finite difference based TALISMAN program was used to simulate this aquifer by UNDP.

Touche & Sivaprakasam (1992) developed a surface-groundwater model to simulate the conjunctive use of Chennai city’s reservoirs and well fields by finite difference method based on the TALISMAN program. They simulated the surface water and groundwater model separately and estimated the reliable yield of surface and groundwater resources. This study has not measured the integrated effect of amount of surface water infiltrate into groundwater and seawater intrusion. Sherif & Singh (1999) assessed climate change on groundwater resources by conceptualizing the aquifer as two-dimensional vertical section using the 2D-FED model. A 50 cm rise in the Bay of Bengal sea level will cause an additional intrusion of 0.4 km. This study not simulated the real field condition as three dimensional density dependent seawater intrusions. Rao et al (2004b) simulated the groundwater flow in the north of Chennai coastal aquifer by using a sharp interface model developed by the United States Geological Survey. Also the simulated volume of the seawater intrusion with and without check dam is estimated. However, this study is not considered the spatial and temporal dynamics of fresh water and salt water.

Ganesan & Thayumanavan (2009) assessed and suggest some of the possible mitigation measures to mitigate seawater intruded aquifer north
of Chennai. Charalambous & Garratt (2009) studied the recharge and the abstraction relationship through finite element model in the Arani - Korttalaiyar groundwater basin. In case of north of Chennai coastal aquifer, a feasibility study on controlling the overland flow and to augment groundwater resources was made by Anuthaman (2009). Anuthaman carried out a research in the A-K basin and around the Chennai Metropolitan area in three stages, 1. Determine the flood hydrograph along the selected nodes of four rivers in A-K basin namely, Adayar, Coovum, Korttalaiyar and Arani. 2. Application of a mathematical model to analyze the regional groundwater flow considering the entire study area as a single entity with the four rivers acting as a recharge boundary using Visual Modflow package to estimate the mass balance of this groundwater basin for two conditions of with and without a recharge by flood attenuation. 3. Evolution of the drainage basin concepts for conjunctive study of the surface and sub-surface flow.

2.5.1 Summary

All the previous hydrological studies carried out in this study area was developed neither the surface water model nor groundwater model and they have not considered the surface water interaction through soil and unsaturated zones to the groundwater resources. Similarly, they do not consider the effects of local geology and surface water interactions on density-dependent groundwater model. As the region receives intensive rainfalls during short periods in monsoons, modelling of an integrated surface water and groundwater flow is necessary to estimate the river flow, infiltration rate and its interaction with the aquifers. It is vital to characterize the aquifer systematically and to assess the measures available to mitigate seawater intrusion in this aquifer. Further, all these studies have not assessed the various recharge options that are available to overcome the problem of
seawater intrusion which has entered up to a distance of about 14.7 km (Indu et al 2015).

Rajaveni et al (2015) assessed the impact of groundwater recharge and pumping on groundwater head. This study has not considered the integrated approach for the real time modelling. Density difference between the fresh groundwater and saline water play an important role in the seawater intrusion studies which is also the limitation of earlier studies carried out in the north of Chennai coastal aquifer. Also the earlier studies carried out in this area have not considered the projected change in rainfall and sea level rise due to the climate change. The projected change in rainfall needs to be accounted in modelling to assess aquifer response for different pumping and recharge conditions. Hence, the present study was carried out with the objective of developing an integrated approach of rainfall-runoff, infiltration and density-dependent groundwater model for a heavily pumped seawater intruded aquifer in north of Chennai, Tamil Nadu state, India to assess the aquifer response for various recharge, pumping and climate change conditions which is necessary to identify options for sustainable management and possible measures to mitigate the problem of seawater intrusion in this aquifer system.